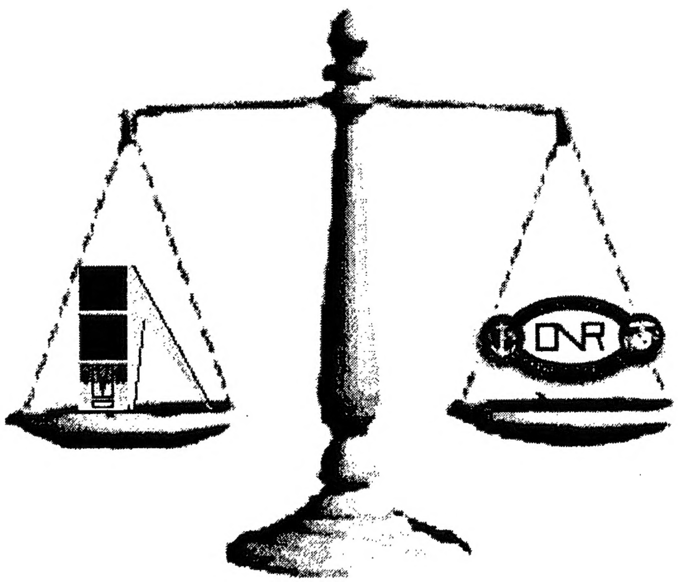
# *A Comprehensive, Robust Design Simulation Approach to the Evaluation/Selection of Affordable Technologies and Systems*




July 21-22, 1999
ONR Affordability Program Grantee Review

Presented By:


**Dr. Dimitri Mavris**

**Dr. Dan DeLaurentis**


Under Grant N00014-97-1-0783


**Aerospace Systems Design Laboratory**
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

# Presentation Outline

1. *Introduction and Research Setting/Summary*

2. *Overall Technical Approach for Affordable Systems Design*

3. *Methods Implementation and Testbed Applications*

4. *Key Advancements in Method Components*

5. *Conclusions/Summary*

# Section 1

1. *Introduction and Research Setting/Summary*

2. *Overall Technical Approach for Affordable Systems Design*

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# ONR-AMPP Goals and ASDL Objectives

## Overall ONR Goal (AMPP program)

Develop methods for measuring and predicting affordability during S&T investment decision making for optimal resource allocation

## Results of Georgia Tech ASDL Research Grant

- A comprehensive, structured, and transparent decision making **methodology** has been developed to guide S&T investment and resource allocation, with the capability for risk reduction, total ownership cost reduction, and performance improvement.

- The baseline tool created to implement this process is called TIES: the *Technology Identification, Evaluation, and Selection* tool
TIES is the research testbed as well as research product !

# ASDL-ONR Objective Mapping

**AMPP Objectives:**

- Facilitate S&T Resource Allocation Decisions ✓
- Enable Early Definition/ Assessment of Weapon System Design Trade Spaces ✓
- Assess Impact of Technology Insertion ✓
- Perform Total Cost of Ownership Prediction and reduction for Navy Weapon Systems ✓
- Define Affordability Metrics ✓
- Predict System Affordability ✓

**ASDL Research Thrusts:**

- Multi-Attribute Decision Making
- Technology Impact Forecasting
- Technology Identification, Evaluation, and Selection
- Joint Multivariate Probabilistic Modeling
- Advances in Soft Computing

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# ONR Grant: ASDL Ph.D. Student/Staff Support

Number of Ph.D. Students Supported: 8

| | |
|---|---|
| Ms. Debora Daberkow (ASDL) | Mr. Oliver Bandte (ASDL) |
| Ms. Danielle Soban (ASDL) | Mr. Andy Baker (ASDL) |
| Ms. Elena Garcia (ASDL) | Ms. Linda Wang (ASDL) |
| Ms. Shobana Murali (Math) | Mr. Noppadon Khiripet (EE) |

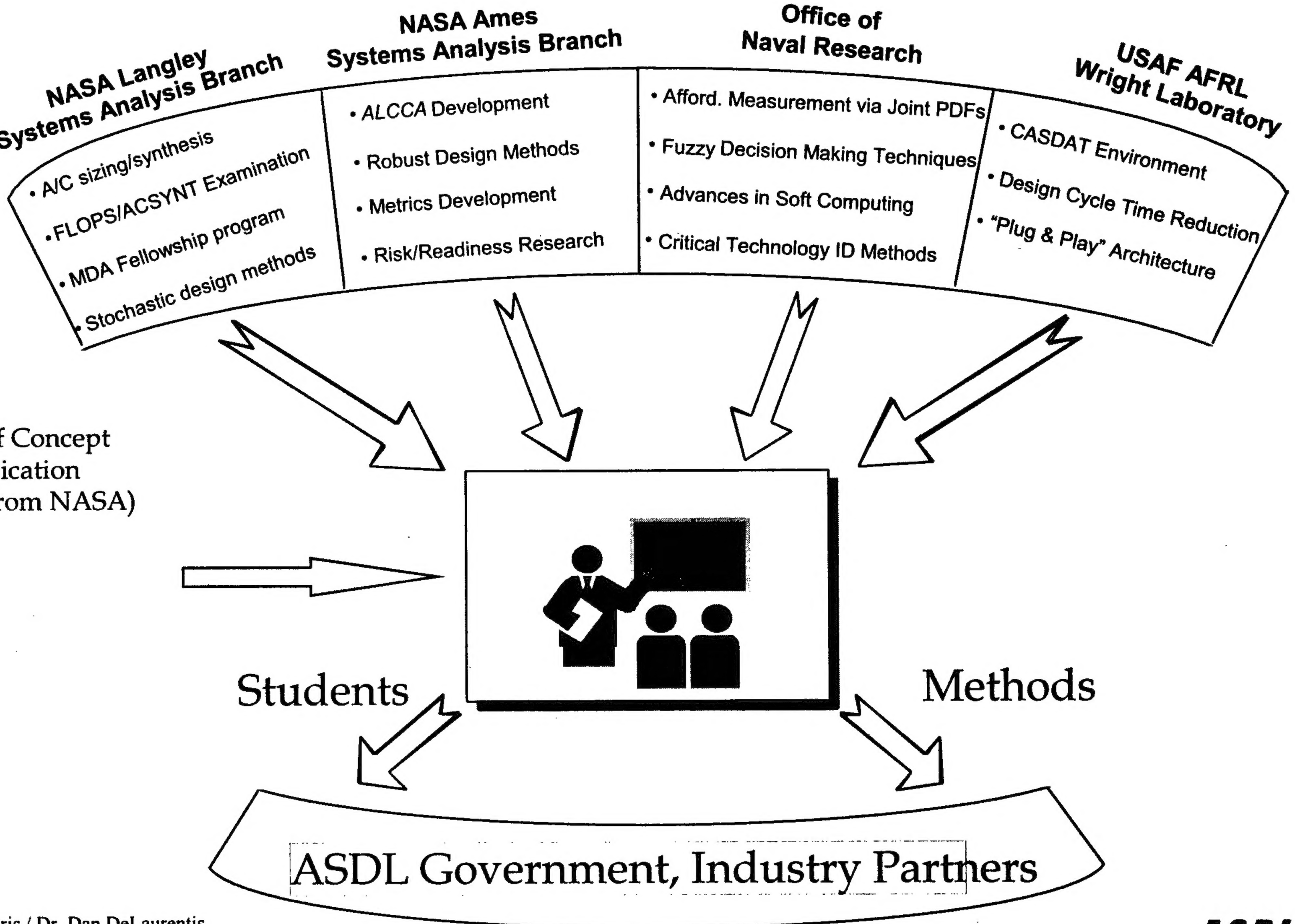
Number of Masters Students Supported: 8

Multidisciplinary Professional Team: 4

| | |
|---|---|
| Dr. Dimitri Mavris (AE) | Dr. Daniel DeLaurentis (AE) |
| Dr. Dan Schrage (AE) | Dr. Mark Hale (AE) |
| Dr. Leonid Bunimovich (Math) | Dr. George Vachtsevanos (EE) |
| Dr. Jimmy Tai(AE) | Dr. Ivan Burdun (AE) |

+ ***Over 40 students exposed to methods in graduate design curriculum***

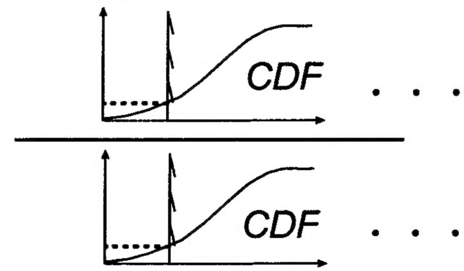
# Collaborative Research Sponsorship



# Definition of Affordability

**Affordability: The ratio of benefits provided or gained from the system over the cost of achieving those benefits**
***In a probabilistic, Modeling & Simulation approach, Risk is inherent in these estimates***

$$S\ \&\ T\ Affordability = \frac{Weapon\ System\ Effectiveness}{Investment\ to\ Achieve\ This\ Effectiveness}$$




## Weapon System Effectiveness- Aircraft Example

**Cost**
- Acquisition cost
- Operation cost
- Maintenance cost
- Aircraft replacement
- Crew replacement training
- RDT&E Cost

**Operational Effectiveness**

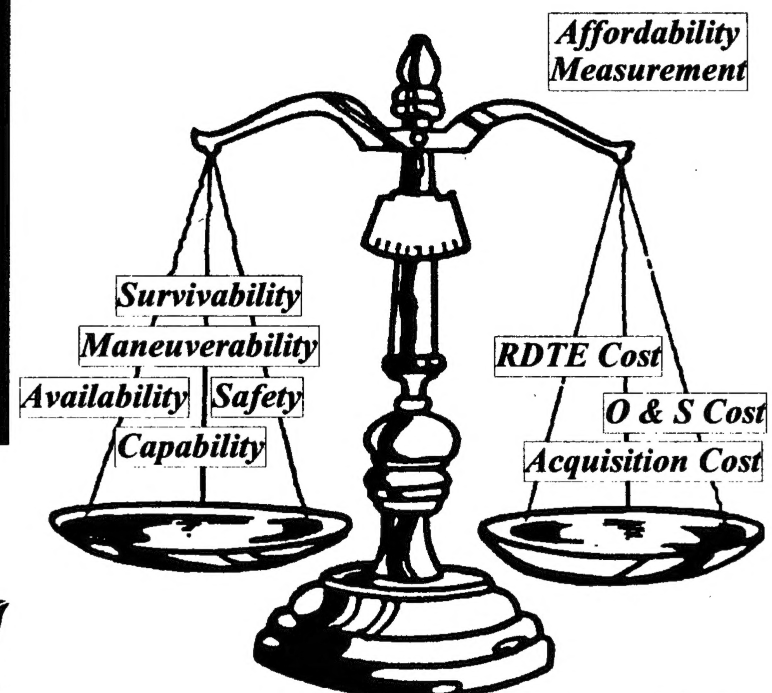
**Survivability**
- Susceptibility
- Vulnerability

**Readiness**
- Maintainability
- Inherent availability
- Reliability
- Logistics support

**Capability**
- Performance
- Maneuverability
- Satisfying mission requirements
- Lethality

**Dependability**
- Safety
- Reliability
- Maintenance defects
- Design defects
- Operations

Effectiveness = $k_1$(Capability)+ $k_2$(Survivability)+ $k_3$(Readiness)+ $k_4$(Dependability) + $k_5$(Life Cycle Cost)

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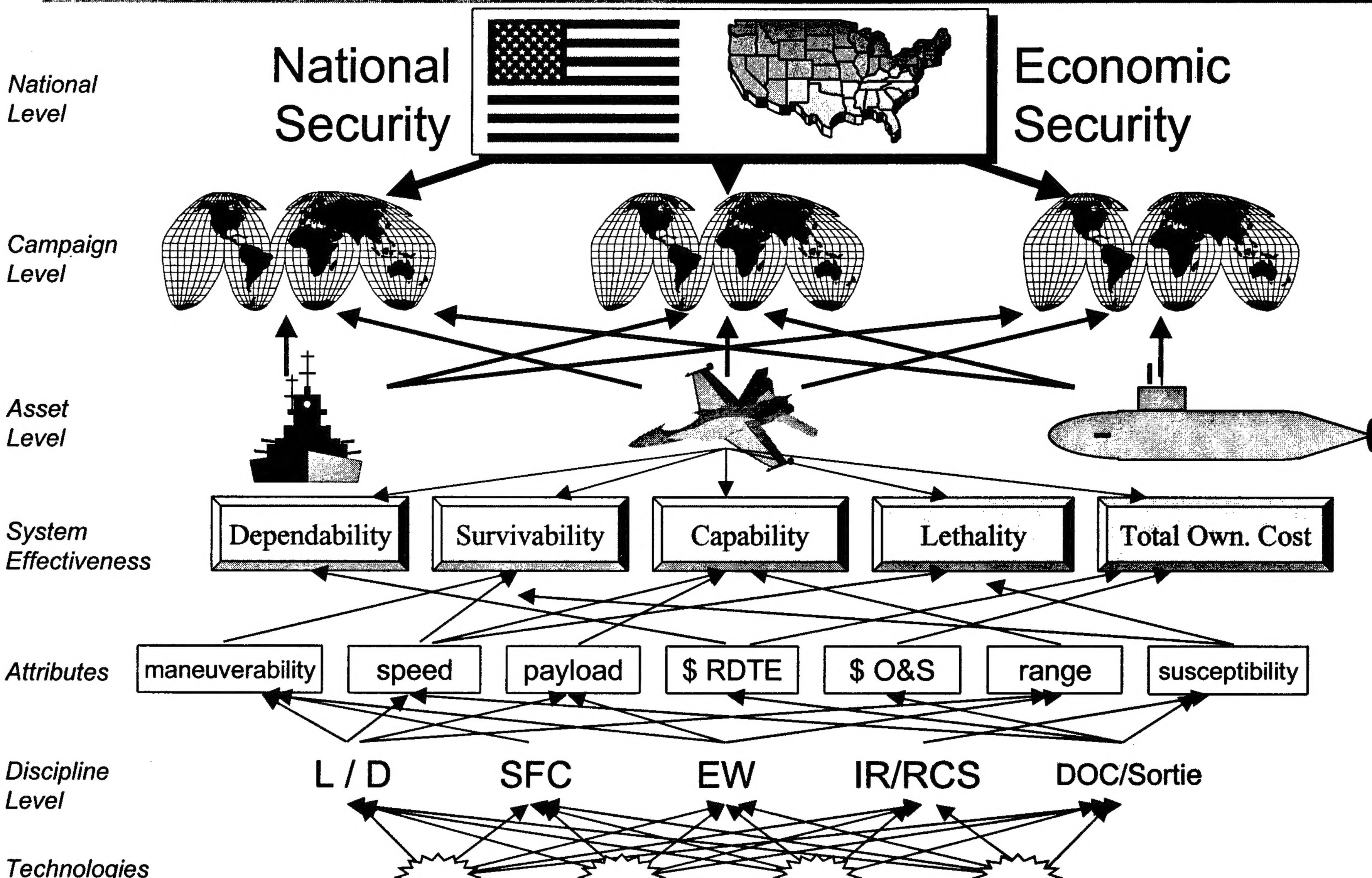
# Science & Technology Return on Investment (ROI)

<u>An Alternate Evaluation Criterion:</u>

$$\frac{\partial\,\text{Benefit}}{\partial\,\text{S\&T Investment}}\;;\;\frac{\partial\,\text{Cost Savings}}{\partial\,\text{S\&T Investment}}\;;\;\frac{\partial\,\text{Risk Reduction}}{\partial\,\text{S\&T Investment}}$$

***ROI*** Assesses the impact that the S&T investment made on the system performance, survivability, safety, ..., developmental, production, support life cycle cost and on averting or reducing risk or by improving the readiness associated with a given technology.

# Problem Definition- Hierarchical Decomposition





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# Technical Areas of Research

ASDL's research for the ONR presented here falls in the following categories:

- Decision-Making methods for Affordability, with and without modeling and simulation capabilities. This area includes:
  - *analysis of alternative concepts and technologies*
  - *joint multivariate probability models for decision making*
  - *multi-attribute methods such as TOPSIS*
  - *decision tree networks with fuzzy inputs.*
- Affordability measurement and prediction (forecasting) of future technology options, in the presence of a variety of uncertainties. This area includes:
  - *Use of Response Surface Models of physics-based analyses*
  - *Uncertainty modeling and use of Fast Probability Integration (FPI)*
  - *Preliminary research into stochastic models and methods*
- Concurrent, physics-based modeling of system requirements and technologies
  - *Nonlinear, constrained equation solver for feasible solutions that trade requirements and technology levels*

***All three of these areas are encompassed in the overall TIES environment***

# Review of Year 1 Results

An innovative, comprehensive method for engineering decision making was created, the Technology Identification, Evaluation, and Selection (TIES) method, populated by:

- *Problem Definition/Brainstorming Tools: QFD, Morphological Matrix, Pugh Matrix*
- *Intelligent Modeling & Simulation and Technology Impact Forecast through Response Surface Methods*
- *Method for rapid assessment of technical feasibility and economic viability*
- *Multi-attribute decision making methods (MADM)*
- *Initiation of a Joint Probability Decision Making (JPDM) model*

Investigation of Advanced Math and Soft Computing Techniques

- *Review and classification of nine emerging techniques*
- *Comparative study of Neural-Network and Response Surface approximations*
- *Employment of Fast Probability Integration (FPI) techniques to assist in probabilistic formulation*
- *Review of advanced tree-network formulations for decision-making under uncertainty and schedule constraints*

# Summary of Year 2 Results

1. Significant enhancements to the TIES affordability environment est. in Year 1
   - *Pilot Studies: Environment prototype for Navy's F-18C, NASA's HSCT, a notional 150 pax transport, and a short-haul civil tiltrotor*
   - *JPDM incorporation and validation; n-variate math model constructed*
   - *Genetic Algorithm for technology combinatorial selection problems*
   - *Fuzzy Decision tree constructed to treat stochastic affordable technology selection problem, an evolution of TIES to include schedule/cost as well as performance*

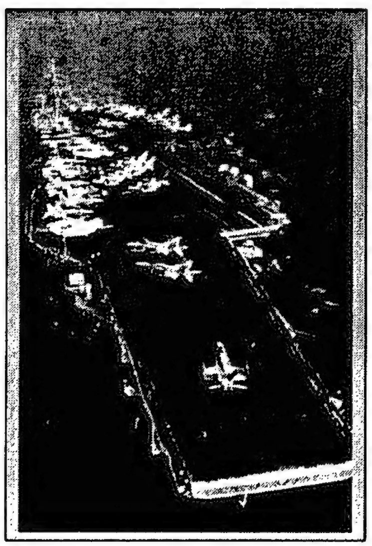
2. Completion of the investigative research into mathematical and soft computing techniques and stochastics, resulting in:
   - *Web-based database of advanced math and soft computing techniques relevant to affordability measurement and prediction, including current investigators, computer codes, and transition status*
   - *Several implementations of methods (Fuzzy sets, GA's, Neural Networks)*
   - *Roadmap towards stochastic methods established, research goals prioritized*

3. A powerful mathematical tool to examine the simultaneous impact of vehicle requirements & technologies has been created and initially tested on a F/A-18C case, including carrier suitability constraints.

4. Methods have been integrated in Graduate level curriculum

# Research Payoffs: Value Added to USN

- Tradeoff requirements vs. technologies *early in design and procurement* phases, with implications for Navy Total Cost of Ownership (TOC) reduction
  - Ability to identify and assess the impact of new technologies for *Resource allocation planning*
    - Probabilistic *assessment of design, technological, and operational uncertainty*
      - Efficient system *feasibility and economic viability assessment*



- *Reduction in design cycle time and cost*
- *Design for affordability* in an IPPD environment
- Design for "cost as an independent variable" *(CAIV)* as a stochastic process
- Initial implementation of affordability methods to F/A-18C and NASA's HSCT, with further validation on Navy systems proposed

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# Section 2

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2. *Overall Technical Approach for Affordable Systems Design - Feasibility/Viability Examination and the TIES Method for Affordable Technology Investment*

3. *Methods Implementation and Testbed Applications*

4. *Key Advancements in Method Components*

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# Decision Making:

## Two Avenues for Technology Assessment

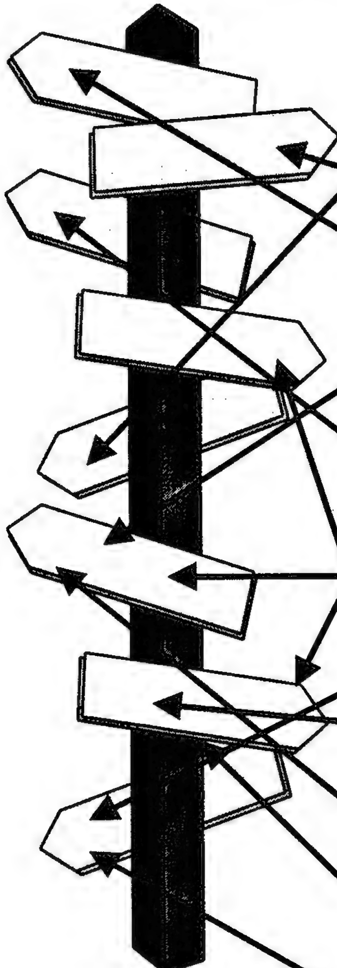
1) Subjective Rankings through QFD, Pugh Diagrams, and Multi-Attribute Decision Making (MADM)

- DoD guiding documents (e.g. DTAPS) & expert opinion are used to establish a mapping of the Navy's warfighting structure
- Through Quality Function Deployment (QFD) and Pugh Diagrams, this mapping is used to subjectively assign importance weights to various technologies accounting for joint warfighting needs
- Multi-Attribute Decision Making (MADM) techniques use results to guide the decision maker to the best solutions

2) Modeling & Simulation (M&S) and Joint Probabilistic Decision Making (JPDM)

- Engineering analyses and physics-based models of technologies are employed in order to obtain objective estimates of technology impacts
- Probabilistic analysis techniques captures uncertainty and risk among multiple, inter-related decision criteria

# Established Techniques + Innovative Methods = *The TIES Affordability Approach*



## Established Techniques

- ★ Response Surface Method (Biology; Ops Research)
- ★ Design of Experiments (Agriculture, Manuf.)
- ★ Quality Function Deployment, Pugh Diagram (Automotive)
- ★ Morphological Matrix (Forecasting)
- ★ MADM techniques (U.S Army, DoD)
- ★ Uncertainty/Risk Analysis (Controls; Finance)
- ★ Simulation-Based Acquisition (DoD Procurement)

## ASDL Innovation

- ★ Feasibility/Viability Identification
- ★ Technology Impact Forecast
- ★ Joint Probabilistic Decision Making
- ★ Stochastic approaches
- ★ Intelligent Integration ⇨ TIES Affordability Meth.

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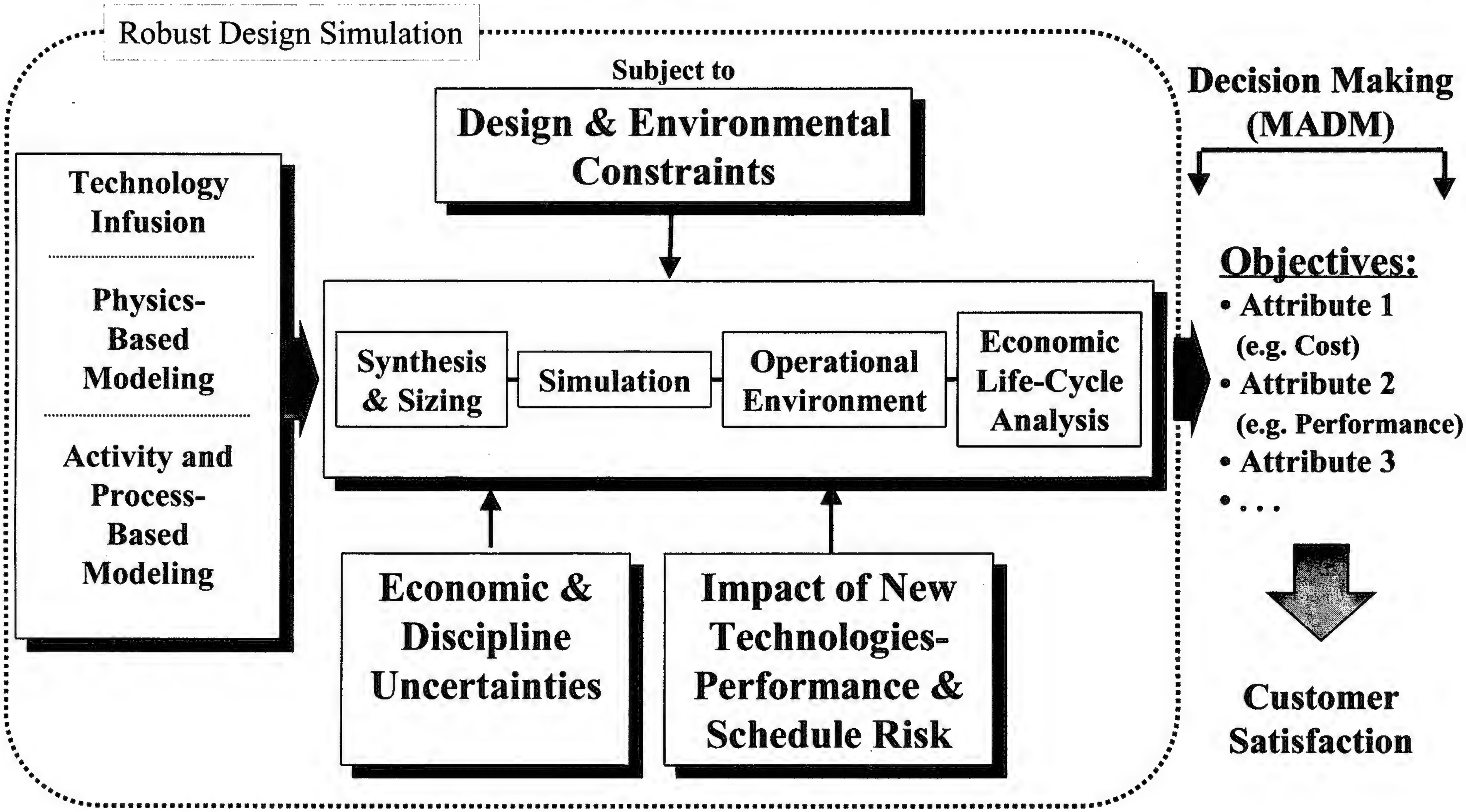
# Physics-Based Modeling and Simulation Environment

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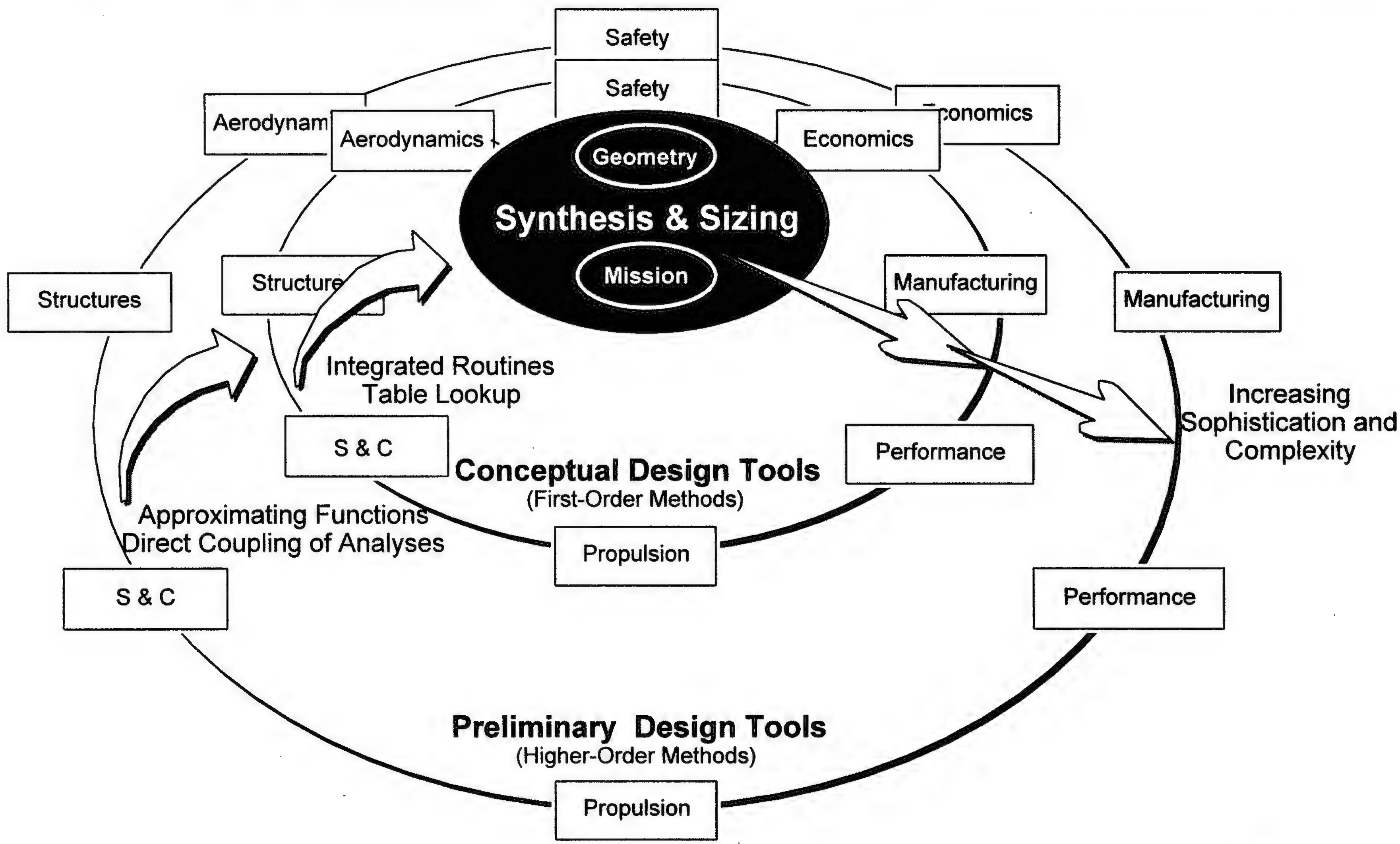
# Creation of a Multi-disciplinary Physics-Based M&S Environment

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# Response Surface Methodology (RSM)

- RSM is a multivariate regression technique developed to model the response of a complex system using a simplified equation
- RSM is based on the design of experiments methodology which gives the maximum power for a given amount of experimental effort
- Typically, the response is modeled using a second order quadratic equation of the form:

$$R = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j$$

Where,

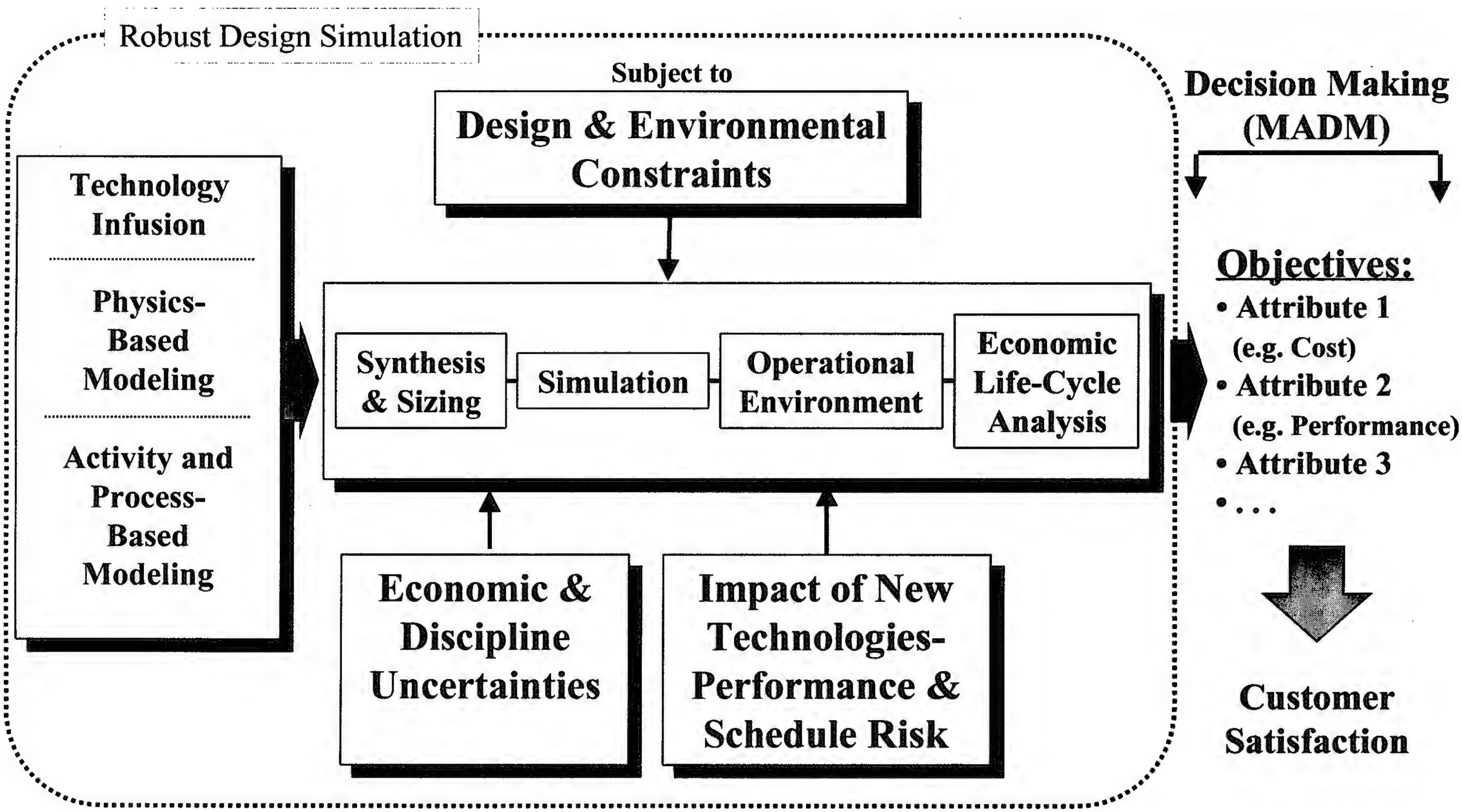
$b_i$ are regression coefficients for the first degree terms
$b_{ii}$ are coefficients for the pure quadratic terms
$b_{ij}$ are the coefficients for the cross-product terms

# Design of Experiments

| Design of Experiments | For 7 Variables | For 12 Variables | Equation |
|---|---|---|---|
| Full Factorial | 2,187 | 531,441 | $3^n$ |
| Central Composite | 143 | 4,121 | $2^n+2n+1$ |
| Box-Behnken | 62 | 2,187 | - |
| D-Optimal Design | 36 | 91 | $(n+1)(n+2)/2$ |

| | Factors | | | |
|---|---|---|---|---|
| Run | $X_1$ | $X_2$ | $X_3$ | Response |
| 1 | -1 | -1 | -1 | $y_1$ |
| 2 | +1 | -1 | -1 | $y_2$ |
| 3 | -1 | +1 | -1 | $y_3$ |
| 4 | +1 | +1 | -1 | $y_4$ |
| 5 | -1 | -1 | +1 | $y_5$ |
| 6 | +1 | -1 | +1 | $y_6$ |
| 7 | -1 | +1 | +1 | $y_7$ |
| 8 | +1 | +1 | +1 | $y_8$ |

# Physics-Based Modeling and Simulation Environment

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# Robust Design

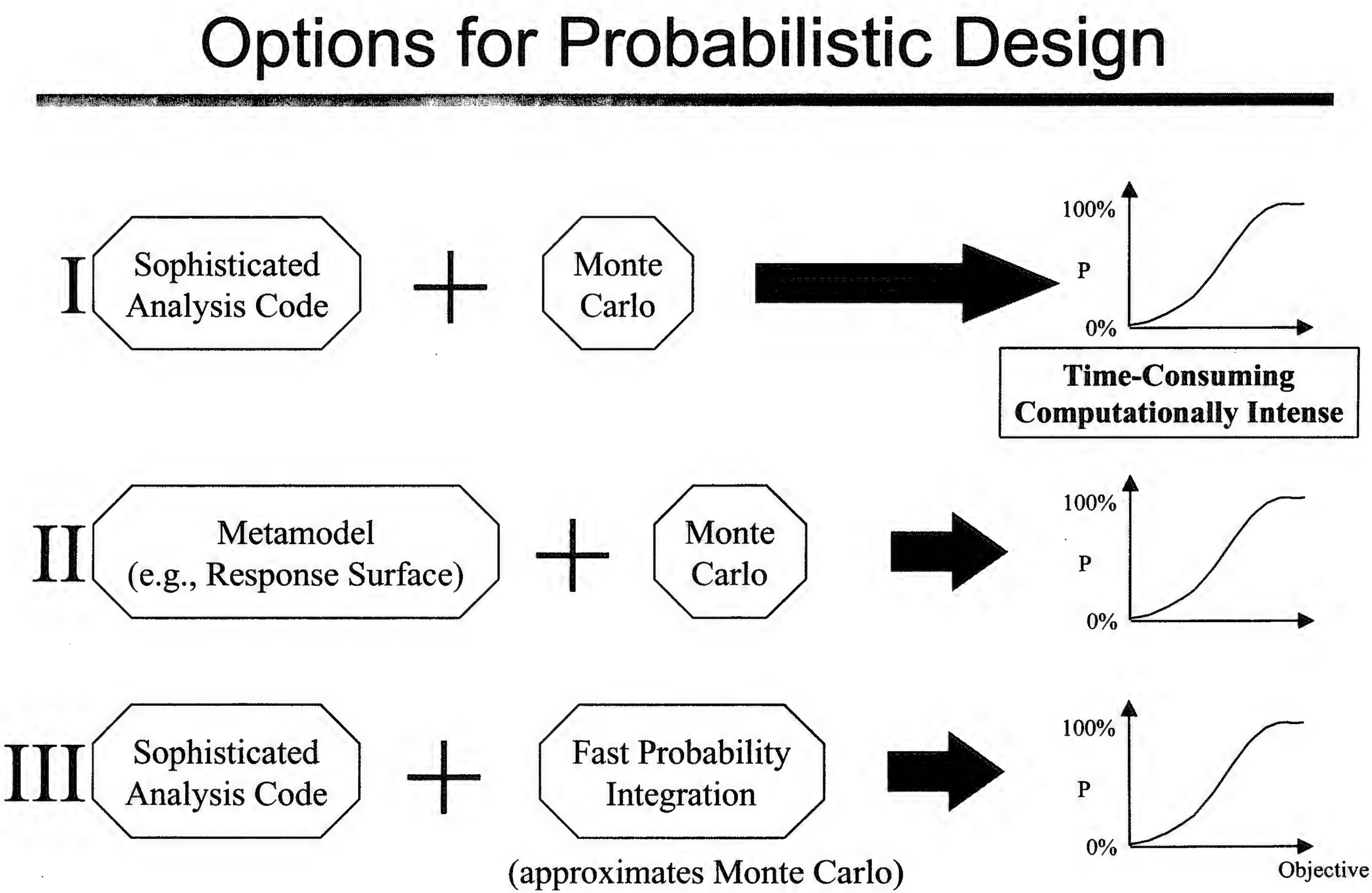
**Robust Design** is the systematic approach to finding *optimum values of design factors* which results in economical designs which *maximize the probability of success*.

A Robust Design is characterized by:

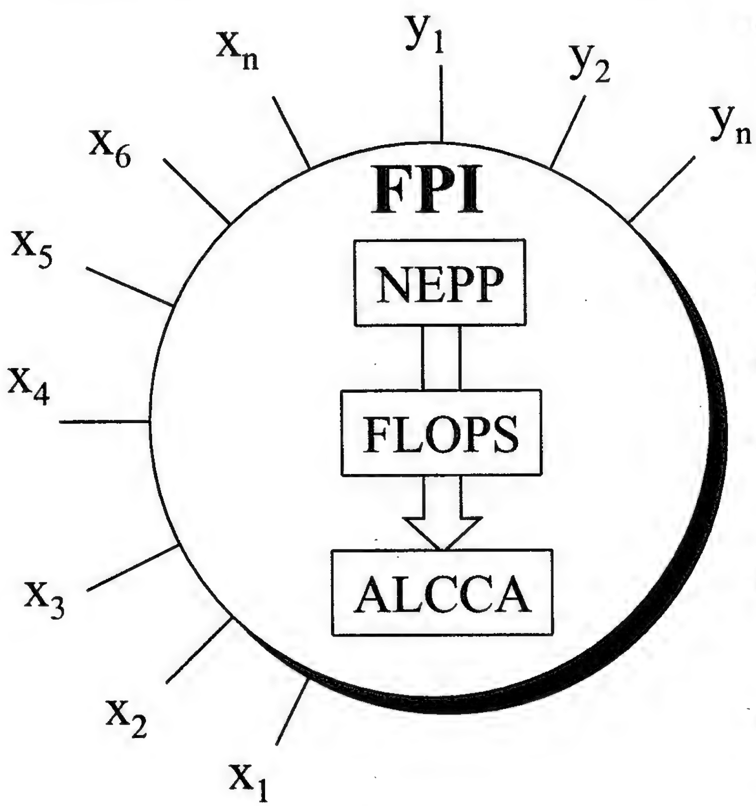
**Technical Feasibility** → satisfies all technical constraints for a given confidence level,

**Viability** → customer's economic targets are also met

# Options for Probabilistic Design



# Fast Probability Integration (FPI)




- FPI manages program execution while handling up to 100 deterministic ($x_i$) or probabilistic ($y_i$) variables, with capability for expansion
- Establishes design feasibility
- Identification of most critical constraints
- Creates probabilistic sensitivity derivatives and CDFs for each objective & constraint
- Assessment of new technologies impact deterministically or probabilistically
- Probabilistic solutions for a set of design variables subject to uncertainty
- Identification of feasible and/or robust solutions, by assigning random distributions to each design variable, within the range of applicability, and allowing for operational and manufacturing uncertainty

# Characterizing the Feasibility/Viability Method

Q1: What are the measures of success ?

Q2: Is a new technology needed ? i.e. Can optimization satisfy the requirements ?

Q3a: What constraints are being violated ?

Q3b: Can constraints be relaxed ?

Q3c: Can requirements be relaxed? Can they be manipulated/examined simultaneously ?

Q3d: What discipline metric is responsible for this violation ?

Q4a: What is the mapping between technologies and metrics, including adverse effects ?

Q4b: What is the confidence associated with a technology estimate ?

Q4c: What is the optimal resource allocation (including combinations of technologies) ?

Q4d: Multi-Attribute Decision Making methods (MADM) yields best mix of technologies ?

Q5: With technologies and confidence estimates chosen, return to full analysis. Can final design space exploration and robust design optimization improve the result ?

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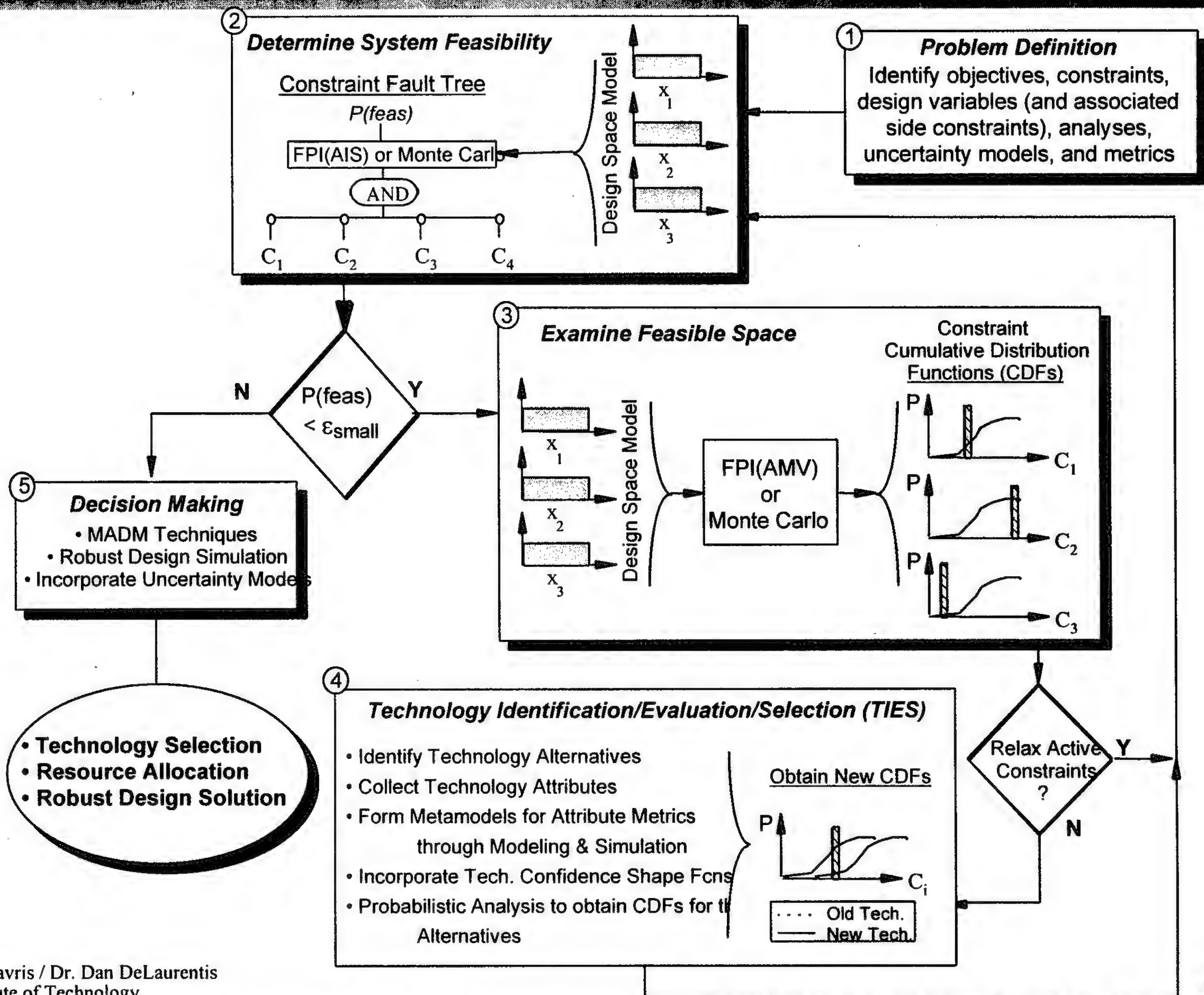
# Roadmap to System Affordability

## Achieving Technical Feasibility & Economic Viability





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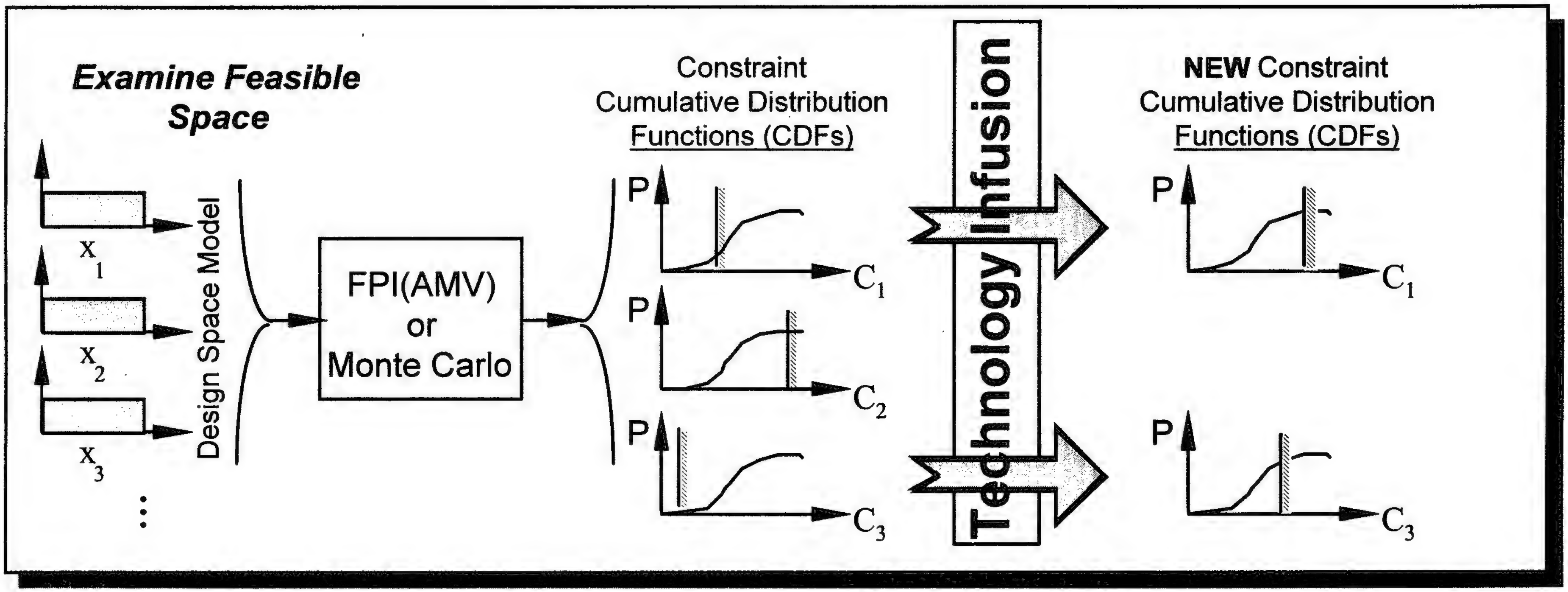
# Feasible Space Examination-
## Technology Infusion

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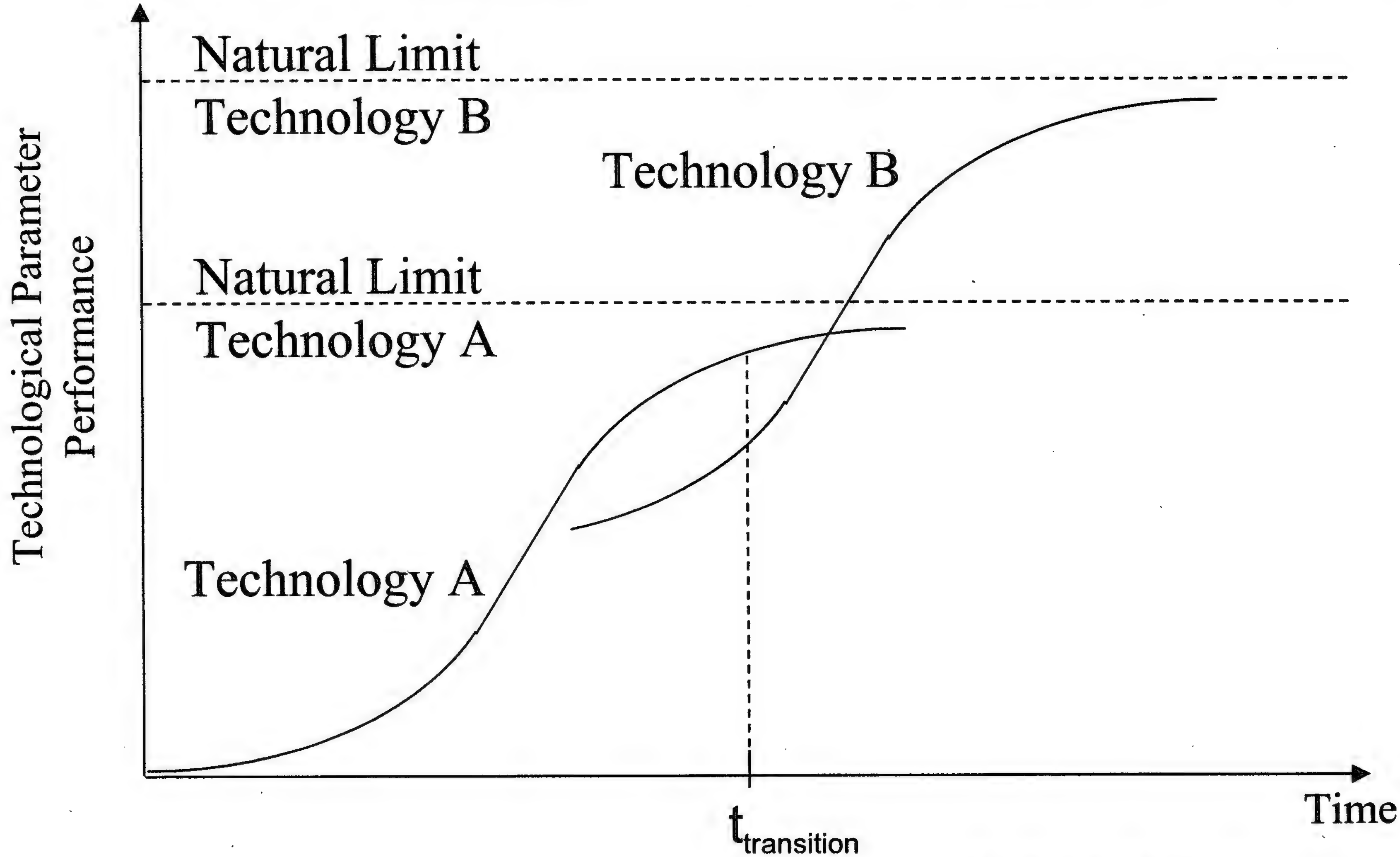
# Technology Substitution




Reference: Twiss, 1992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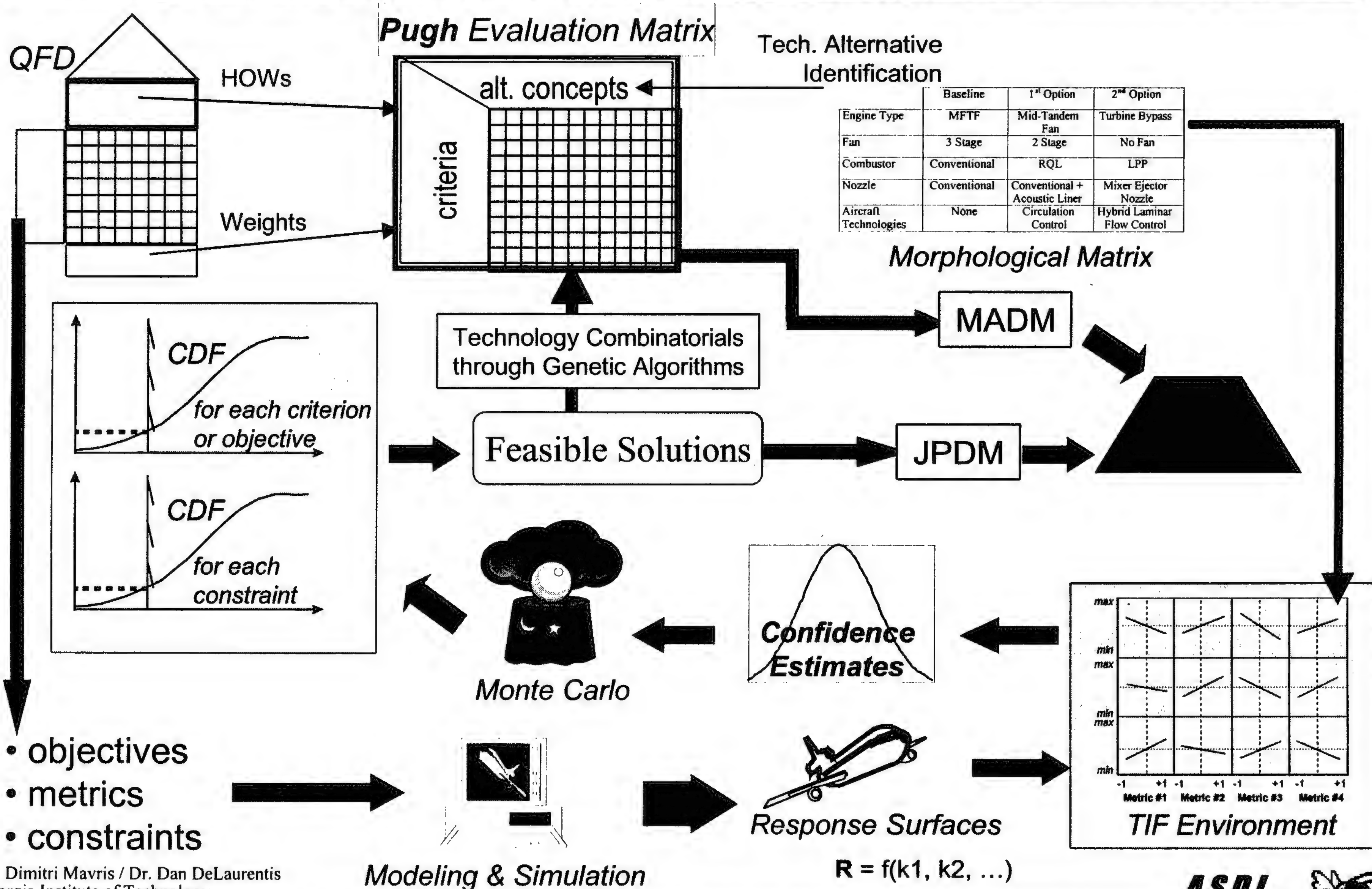
# Technology Identification Evaluation Selection (TIES)




| | Baseline | 1[st] Option | 2[nd] Option |
|---|---|---|---|
| Engine Type | MFTF | Mid-Tandem Fan | Turbine Bypass |
| Fan | 3 Stage | 2 Stage | No Fan |
| Combustor | Conventional | RQL | LPP |
| Nozzle | Conventional | Conventional + Acoustic Liner | Mixer Ejector Nozzle |
| Aircraft Technologies | None | Circulation Control | Hybrid Laminar Flow Control |

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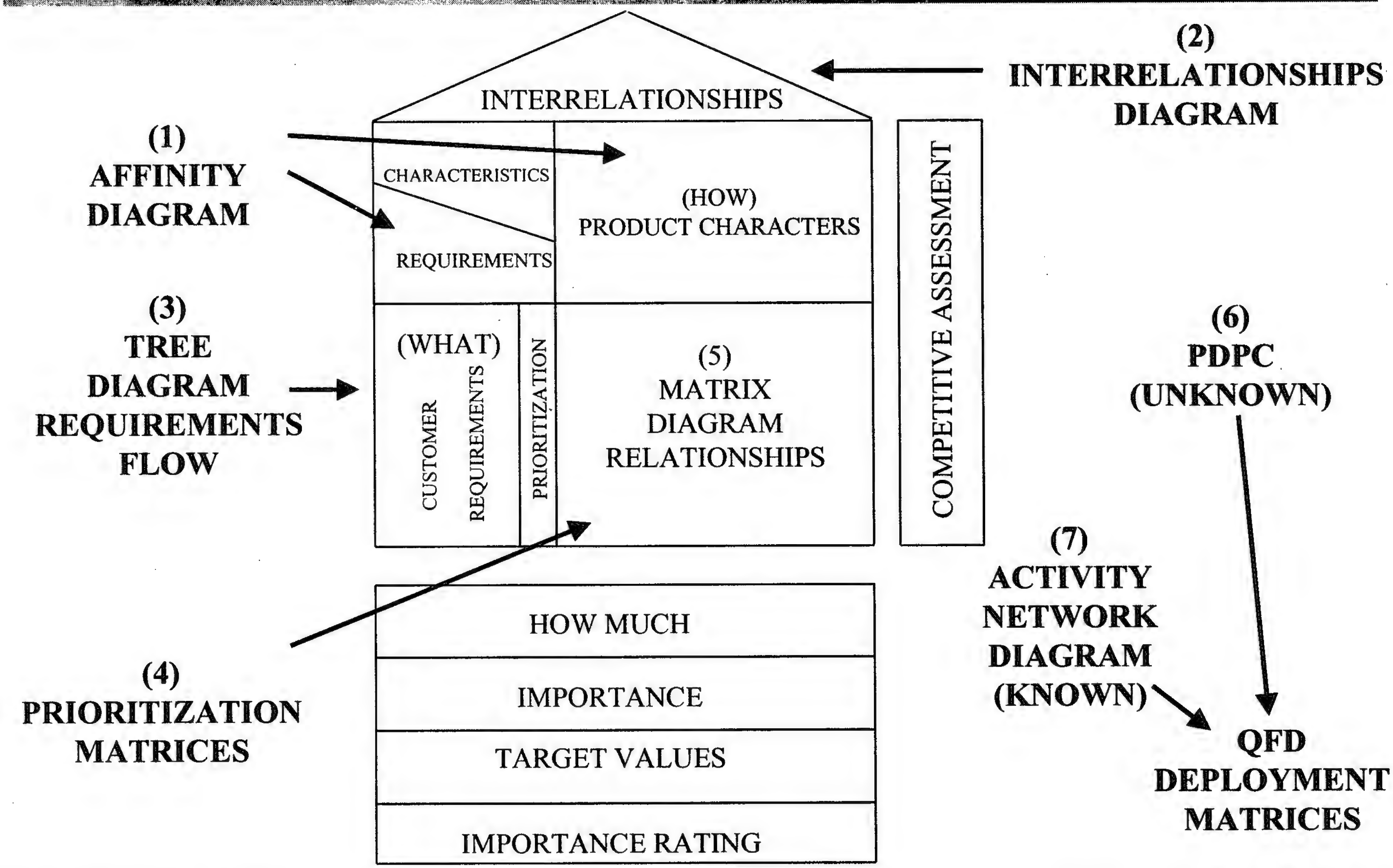
# How the Seven Management and Planning Tools Relate to Quality Function Deployment



# Morphological Matrix

| | Alternatives / Characteristics | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Config | Vehicle | Wing & Tail | Wing & Canard | Wing, Tail & Canard | Wing |
| | Fuselage | Cylindrical | Area Ruled | Oval | |
| | Pilot Visibility | Synthetic Vision | Conventional | Conventional & Nose Droop | |
| Mission | Range (nmi) | 5000 | 6000 | 6500 | |
| | Passengers | 250 | 300 | 320 | |
| | Mach Number | 2 | 2.2 | 2.4 | 2.7 |
| Propulsion | Type | MFTF | Turbine Bypass | Mid Tandem Fan | Flade |
| | Fan | None | 1 Stage | 2 Stage | 3 Stage |
| | Combustor | Conventional | RQL | LPP | |
| | Nozzle | Conventional | Conventional & Acoustic Liner | Mixed Ejector | Mixer Ejector & Acoustic Liner |
| Aero | Low Speed | Conventional Flaps | Conventional Flaps & Slots | C C | |
| | High Speed | Conventional | LFC | NLFC | HLFC |
| Struct | Materials | Aluminum | Titanium | High Temp. Composite | |
| | Process | Chordwise Stiffened | Spanwise Stiffened | Monocoque | Hybrid |

# Pugh Evaluation Matrix

## Qualitative Example

| | Evaluation Criteria | Alternative Concept 1 | 2 | 3 | 4 | ... | n |
|---|---|---|---|---|---|---|---|
| Airline Economics | $/RPM | + | - | - | + | | |
| | Acquisition Price | + | - | + | S | | Datum Point |
| | Engine Price | - | + | - | - | | |
| | DOC/trip | S | + | + | - | | |
| Manufacturer Economics | Sunk Cost | + | - | - | S | | |
| | Break Even Unit | + | - | - | + | | |
| Environmental | EPNLdB $SL_n$ | + | + | - | - | | |
| | EPNLdB $TO_n$ | - | + | - | - | | |
| | EPNLdB $FO_n$ | + | + | - | - | | |
| Reliability Maintainability | MTBF | + | + | - | + | | |
| | MTTR | + | - | S | + | | |
| | MMH/FH | S | S | + | S | | |
| | Risk | + | S | - | - | | |
| | $\Sigma+$ | 9 | 6 | 3 | 4 | ... | |
| | $\Sigma-$ | 2 | 5 | 9 | 6 | ... | |
| | $\Sigma S$ | 2 | 2 | 1 | 3 | ... | |

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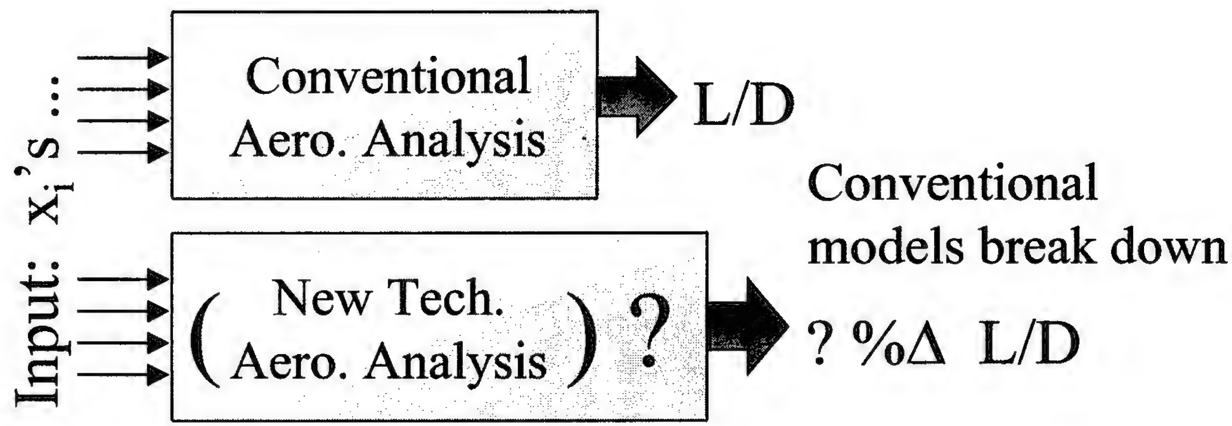
# Mapping Responses to Discipline Metrics via Physics-Based M&S

***Purpose: To Open Feasible Space***

- Formulation in terms of elementary variables does not lend itself to disciplinary or multidisciplinary technology assessment




- The assessment of new technologies must be addressed through the disciplinary metrics (or technology "k" factors) since a mathematical formulation is not yet available

$$\textit{constraints/objectives} = f(k\_L/D_{sub}, k\_L/D_{sup}, k\_C_{Lmax}, k\_T1, k\_SFC_{sub}, \ldots)$$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# Technology Impact on Metrics

- New technology opens the range of the affected metric through a k-factor:

  $\mathbf{L/D_{new} = k_{L/D}\, L/D_{old}}$ ; where $k_{L/D} = 0.9 \ldots 1.2$ is based on Question 10.
- Select ranges for all metrics affected by new technologies
- The technology is applied to a fixed baseline configuration
- Create a DoE to establish .... for each new technology considered

| $k_{L/Dsub}$ | $k_{L/Dsup}$ | $k_{SFC}$ | $k_n$ | $/RPM | TOGW | $V_{app}$ | $R_n$ |
|---|---|---|---|---|---|---|---|
| .9 | 1.05 | 0.95 | | 0.125 | 809,781 | 119 | |
| .9 | 1.05 | 0.85 | | 0.129 | 825,432 | 121 | |
| .9 | 0.85 | 0.95 | | 0.137 | 755,593 | 117 | |
| .95 | 0.85 | 0.85 | | 0.133 | 791,024 | 122 | |
| : | : | : | : | : | : | : | : |

- Create RSE based on uncorrelated metrics, since configuration is fixed and metric improvements ($k_m$'s) are selected independently

# Technology Estimates

## Addressing Technology Benefits, Penalties and Confidence

1. Create functional relationships between Objectives/Constraints and technology metrics

$$\underline{\text{Objective}} = f(L/D_{cruise},\ L/D_{TO},\ C_{Lmax},\ W_{wing},\ SFC,\ MMH/FH,\ \ldots)$$

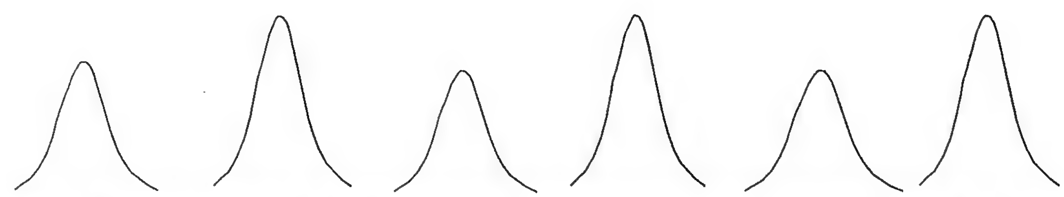
$$\underline{\text{Constraint}} = f(L/D_{cruise},\ L/D_{TO},\ C_{Lmax},\ W_{wing},\ SFC,\ MMH/FH,\ \ldots)$$

2. Model technology benefits and penalties through metric "k-factors"

(Step Change in Mean) +10% +5% +7% -3% +5% -5%

3. Assign probability distributions to the technology metrics to develop confidence estimates and CDFs

(Variability)



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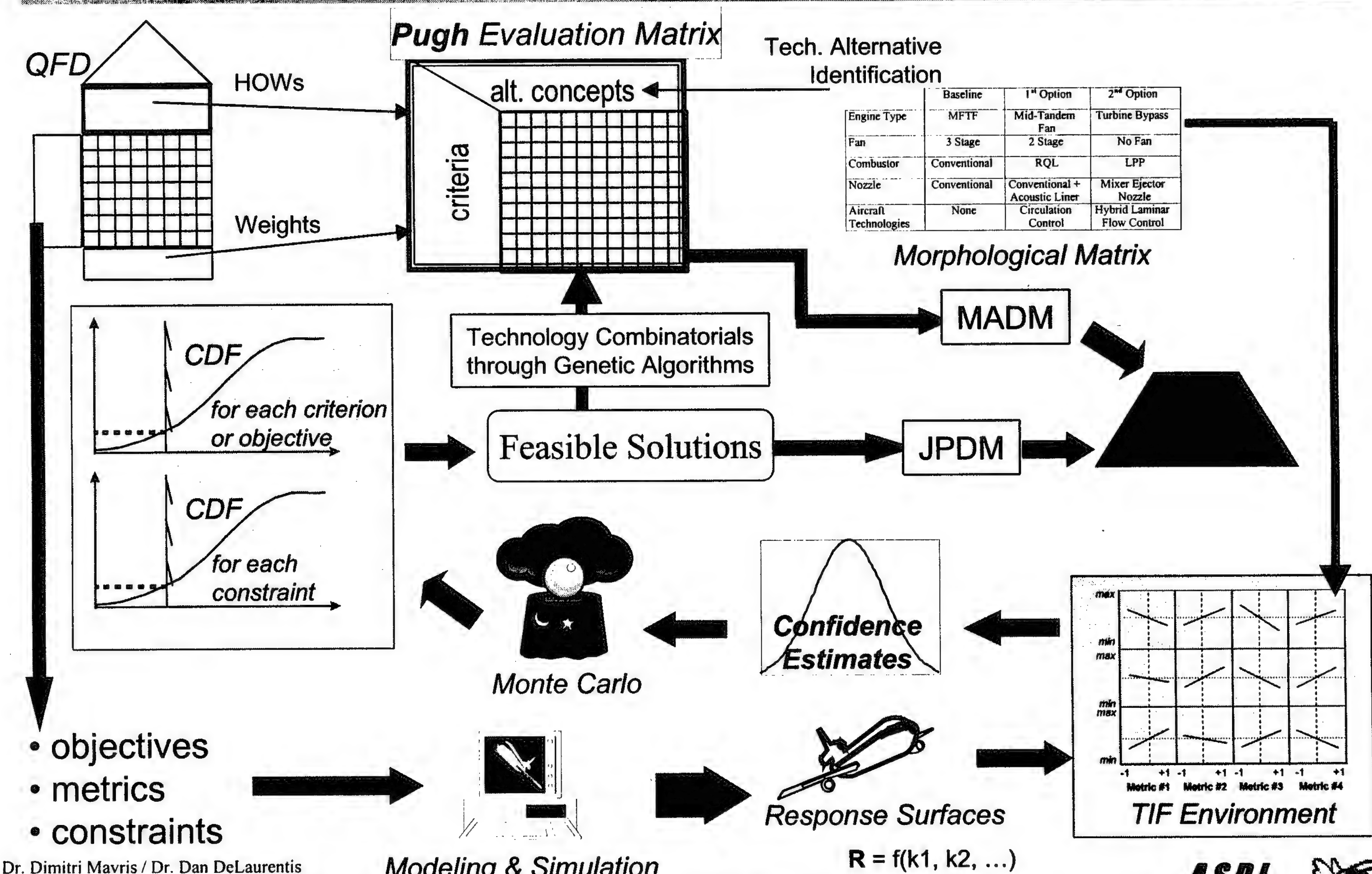
# Technology Identification Evaluation Selection (TIES)




| | Baseline | 1st Option | 2nd Option |
|---|---|---|---|
| Engine Type | MFTF | Mid-Tandem Fan | Turbine Bypass |
| Fan | 3 Stage | 2 Stage | No Fan |
| Combustor | Conventional | RQL | LPP |
| Nozzle | Conventional | Conventional + Acoustic Liner | Mixer Ejector Nozzle |
| Aircraft Technologies | None | Circulation Control | Hybrid Laminar Flow Control |

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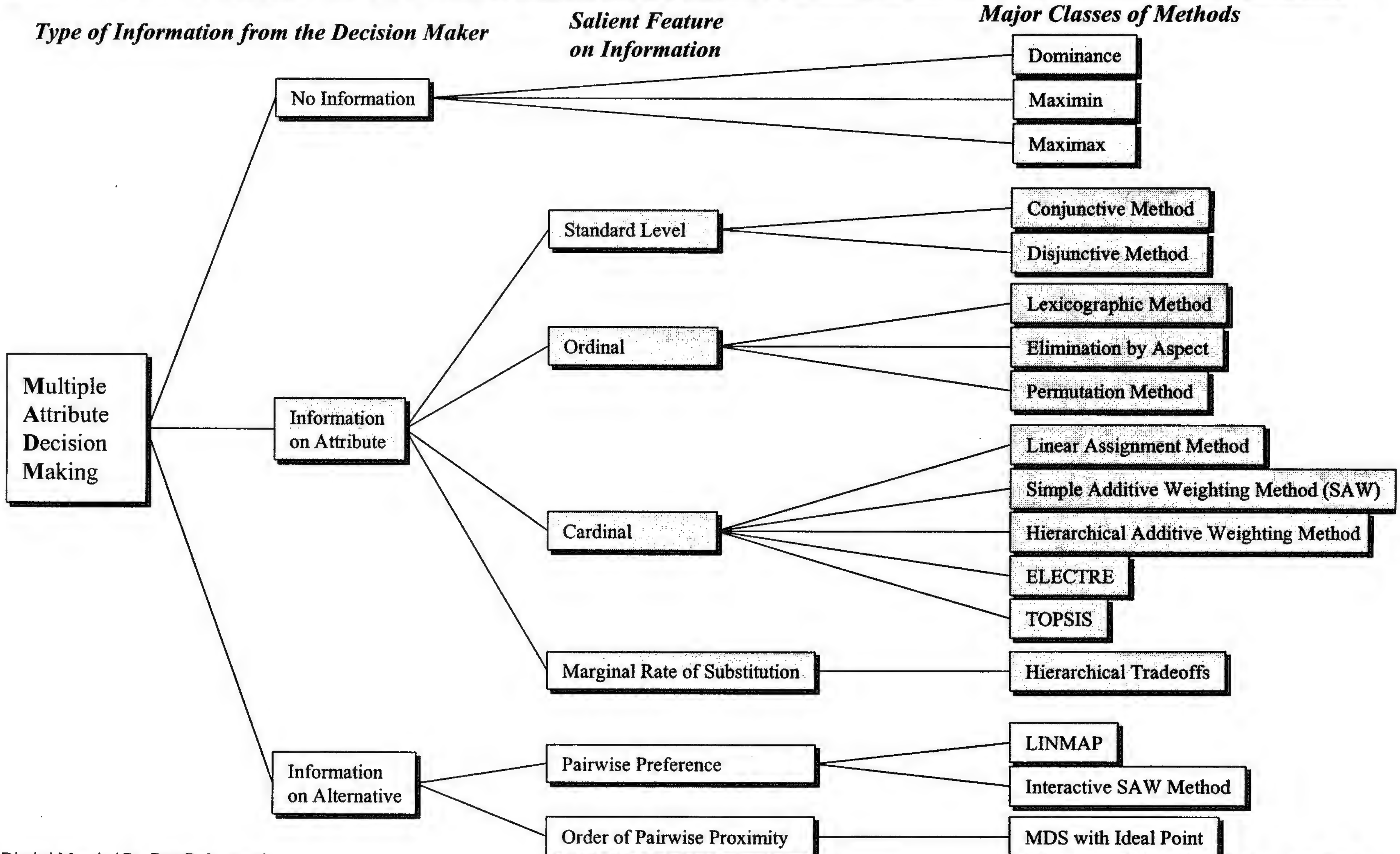
# The MADM Techniques

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# A MADM Choice: TOPSIS

**T**echnique for **O**rder **P**reference by **S**imilarity to **I**deal **S**olution (TOPSIS)

- compensatory and compromising method utilizing preference in the form of weights $w_j$ for each criterion
- best alternative has shortest distance to ideal solution and farthest away from negative-ideal solution

Advantages:

- simplicity
- indisputable ranking obtained

Disadvantages:

- dependent on cardinal information, such as weights
- solution highly dependent on values
- criteria have to have a monotonically increasing or decreasing utility to the decision-maker

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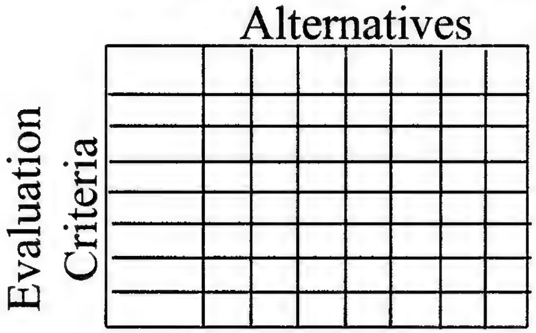
# Multi-Attribute Decision Making (MADM)

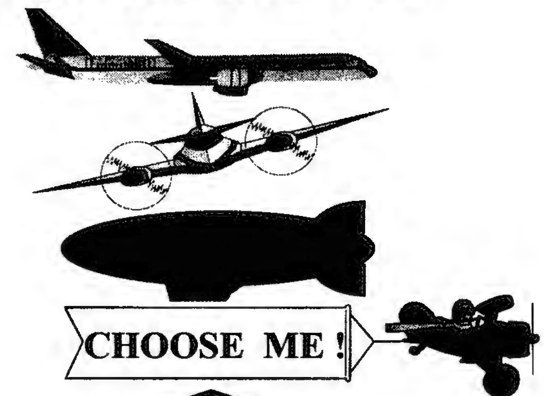
## Pugh Matrix



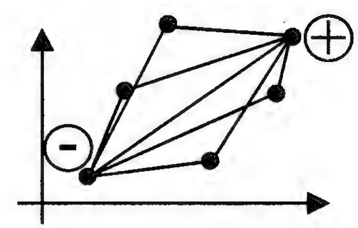

## +/- Ideal Solution

Based on best criteria values

## Ranked Alternatives




## Euclidean Differences

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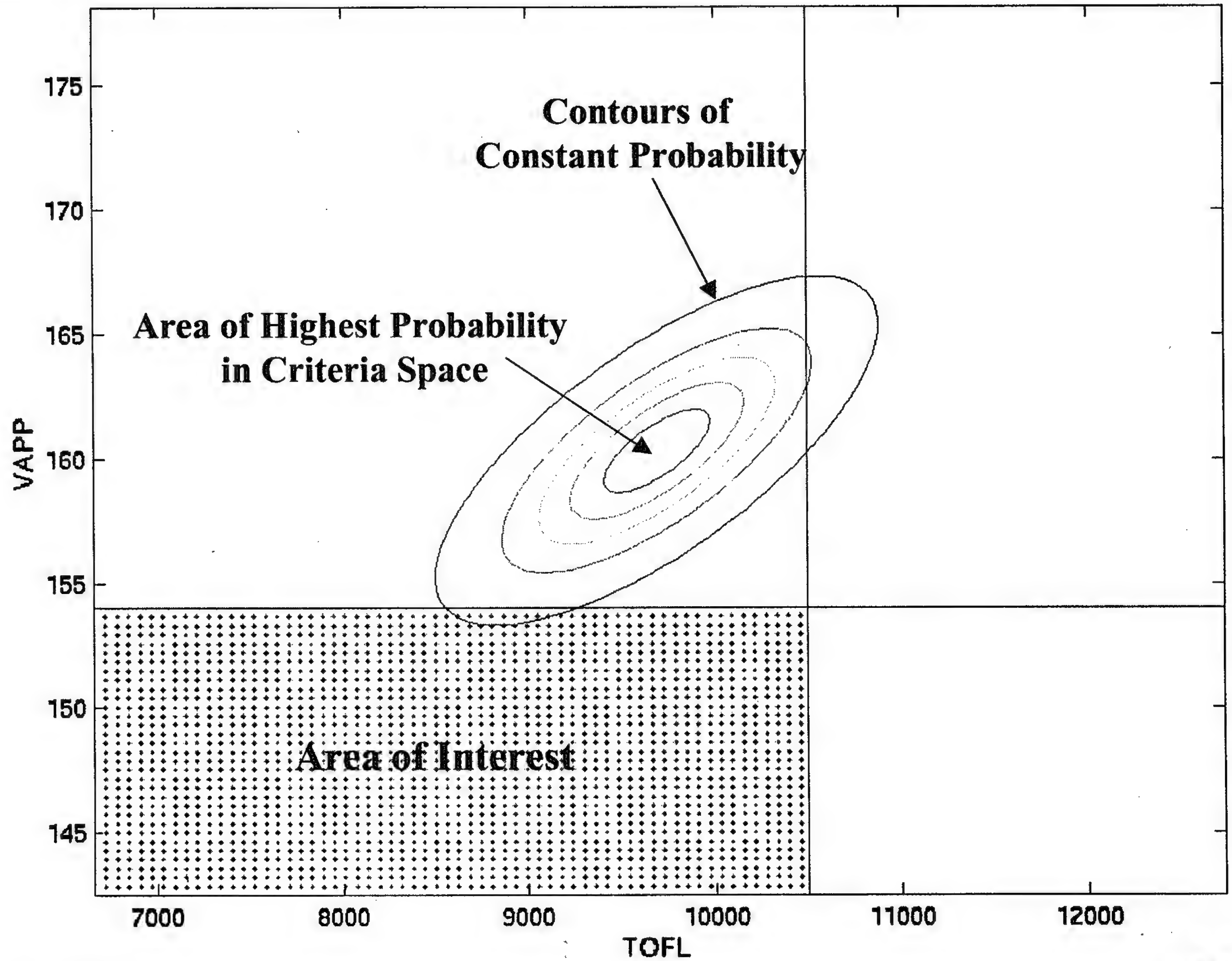
# Joint Probability Density Function - 2D

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# Section 3

*1. Introduction and Research Setting/Summary*

*2. Overall Technical Approach for Affordable Systems Design*

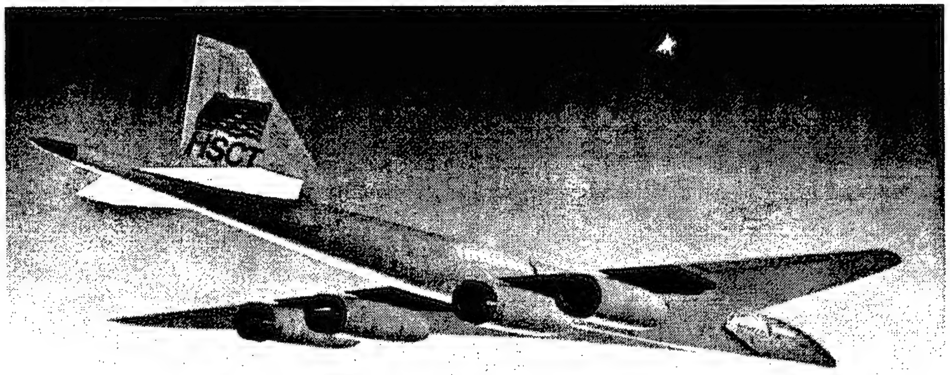
*3. Methods Implementation and Testbed Applications*

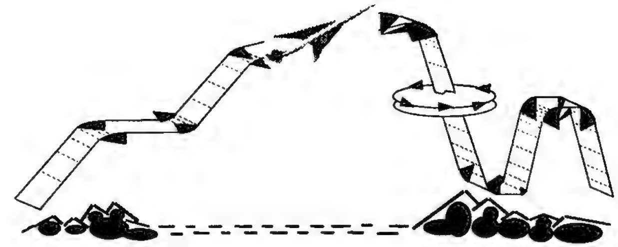
- *Design Space Exploration (Feasibility Determination for a High Speed Civil Transport)*
- *TIES Implementation (Technology Selection for an Advanced 150pax Transport)*
- *Joint Probabilistic Decision Making (JPDM)*
- *Simultaneous Examination of Requirements and Technologies (F/A-18C Testbed)*

*4. Key Advancements in Method Components*

*5. Conclusions/Summary*

# High Speed Civil Transport (HSCT)



- Cruise Mach Number of 2.4
- Range of 5000 nm.
- Carry 300 passengers
- Powered by four engines capable of cruising supersonically without afterburner
- Able to make two round trips to Europe or Pacific Rim in the same amount of time as one trip for a subsonic transport

# HSCT Challenges

- Environmental Constraints
  - Engine that is sized to cruise violates FAA noise regulations
  - Nitrogen Oxide emissions harm the ozone layer

- Performance Constraints
  - Poor takeoff and landing characteristics
  - High Mach numbers require special heat-resistant materials
- Economic Constraints
  - Will require a fare premium
  - Will have a high acquisition cost
  - Will require a large initial investment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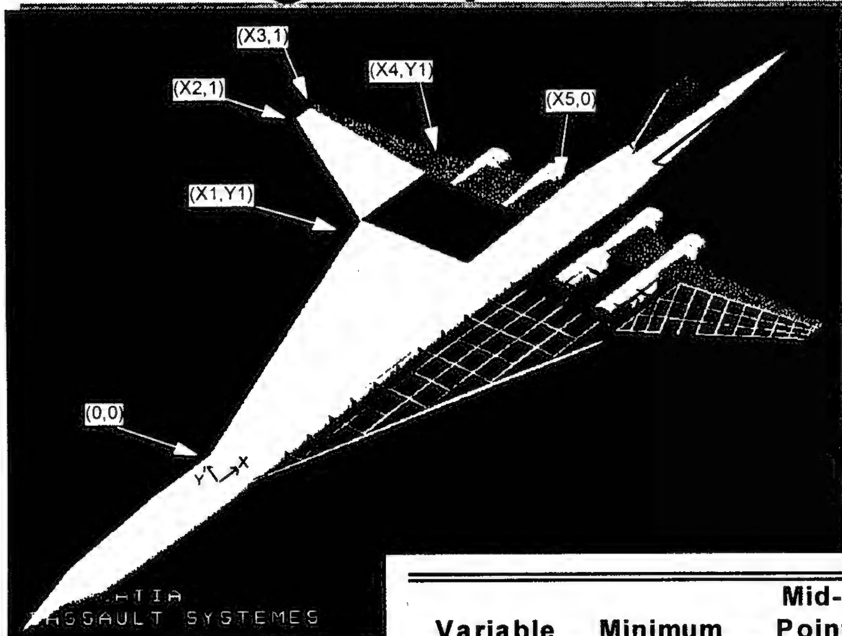
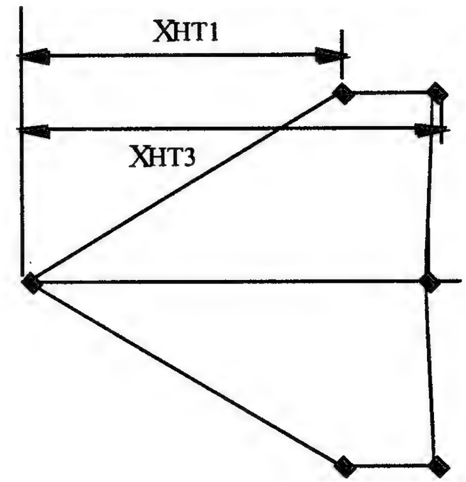
# High Speed Civil Transport (HSCT)




| Variable | Minimum | Mid-Point | Maximum | Remarks |
|---|---|---|---|---|
| X1 | 1.54 | 1.615 | 1.69 | Kink LE x-location, normalized by wing semi-spa |
| Y1 | 0.44 | 0.51 | 0.58 | Kink LE y-location, normalized by wing semi-spa |
| X2 | 2.10 | 2.23 | 2.36 | Tip LE x-location, normalized by wing semi-span |
| X3 | 2.40 | 2.49 | 2.58 | Tip TE x-location, normalized by wing semi-span |
| X4 | 2.19 | 2.275 | 2.36 | Kink TE x-location, normalized by wing semi-spa |
| X5 | 2.19 | 2.345 | 2.50 | Root Chord, normalized by wing semi-span |
| XWING | 26% | 28% | 31% | wing position, % fuselage length |
| SW | 8500 | 9000 | 9500 | wing ref. area, square feet |
| XTAIL | 82% | 84.7% | 87.4% | horizontal tail position, % fuselage length |
| ST | 875 | 922.5 | 970 | horizontal tail ref. area, square feet |
| XHT1 | 0.95 | 1.18 | 1.20 | normalized by HT semi-span |
| XHT3 | 1.90 | 2.00 | 2.10 | normalized by HT semi-span |
| CG | 56% | 57.5% | 59% | CG, %fuselage |

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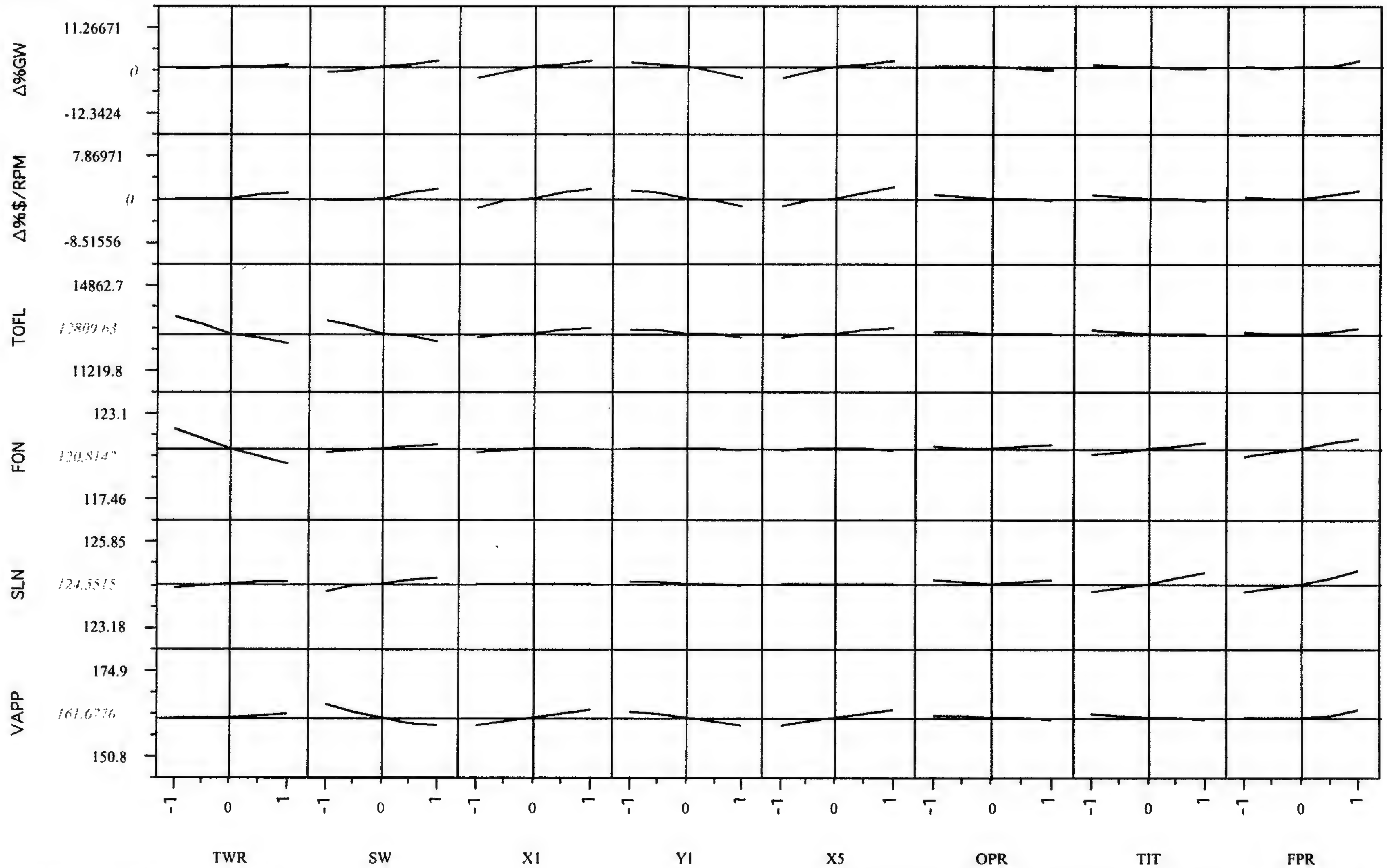
# Prediction Profiles for the HSCT System Level Constraints

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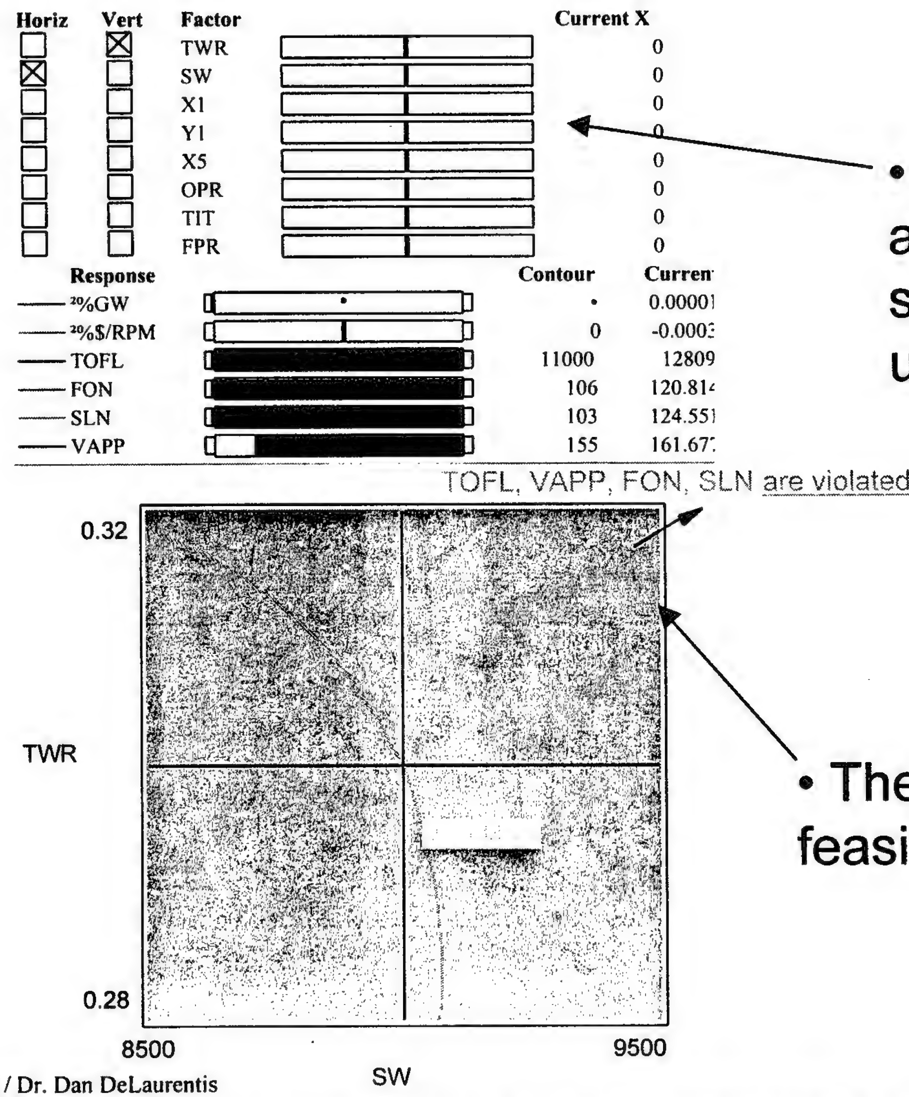
# No Feasible Design Space Due to TOFL, VAPP, FON, and SLN




- The slide bars can be used to adjust the design variable settings, and the design plot is updated in real time.
- The design space plot shows no feasible space.

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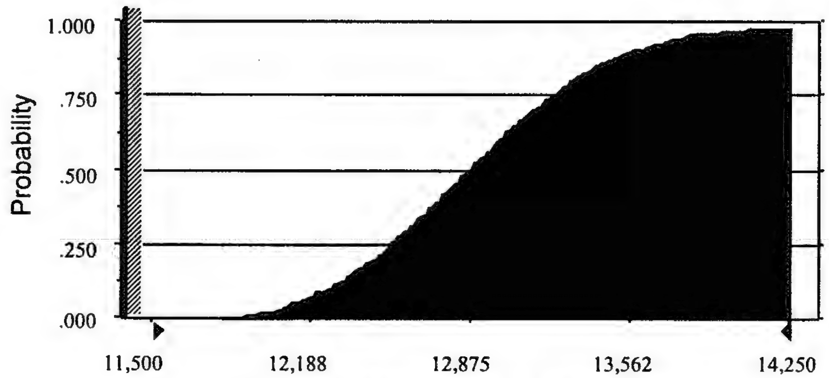
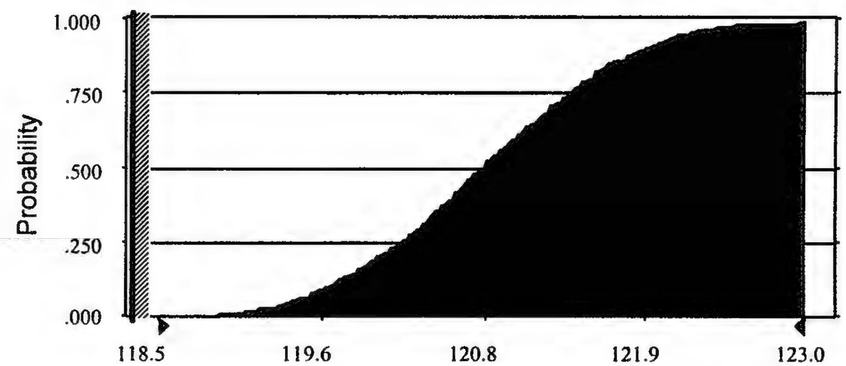
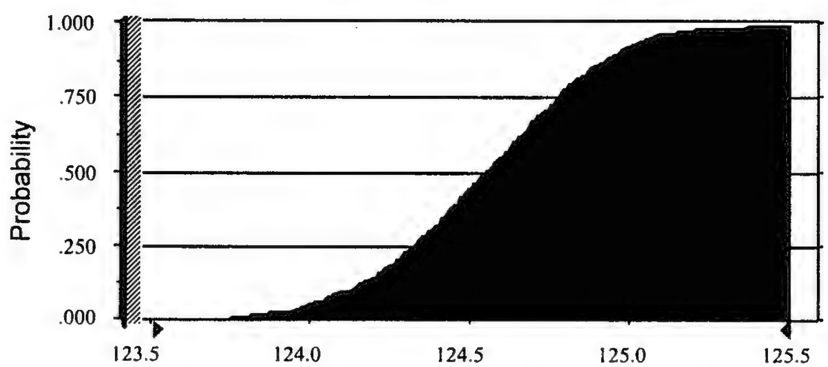
# CDFs for the Four Constraints,

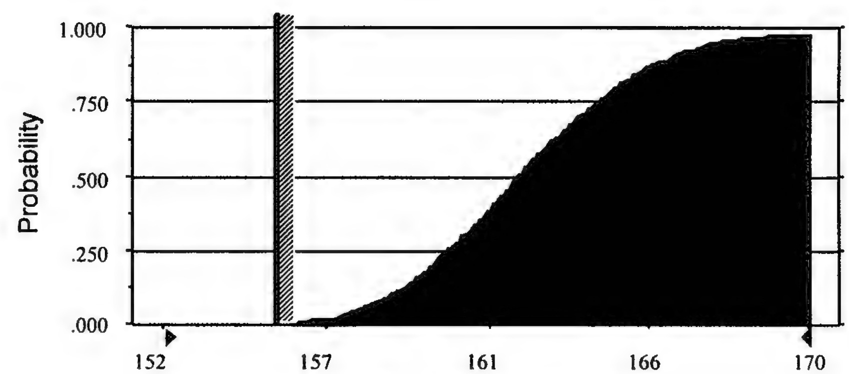
## from Monte Carlo Simulation (5,000 samples)

### All constraints violated throughout initial design space

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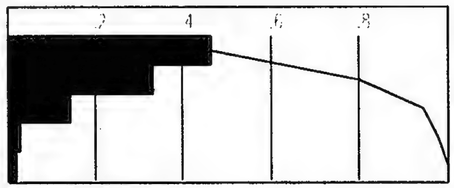
# Pareto Charts: Mission Requirements Sensitivities

## $/RPM

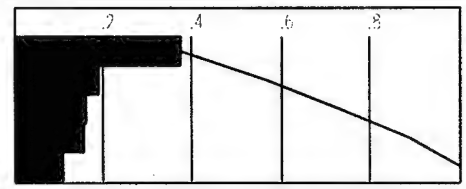
Average Required Yield per Revenue Passenger Mile

| Term | Orthog Estimate |
|---|---|
| PAX | -0.0048359 |
| %SubsMiss | 0.00348035 |
| Des-Range | 0.00151828 |
| S-Wing | 0.00037233 |
| T/W Ratio | 0.00024368 |



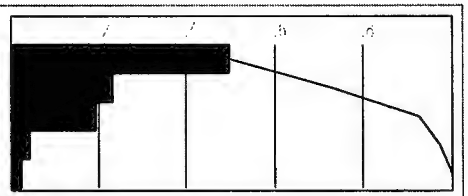
## $-Acquisition Price

| Term | Orthog Estimate |
|---|---|
| Des-Range | 3.5722524 |
| PAX | 1.8383051 |
| %SubsMiss | 1.5712922 |
| T/W-Ratio | 1.4931703 |
| S-Wing | 1.0737944 |



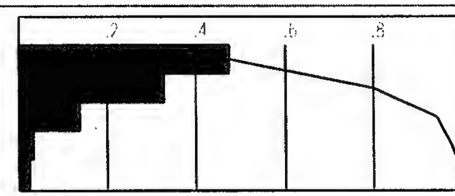
## Gross Weight

| Term | Orthog Estimate |
|---|---|
| Des-Range | 23175.393 |
| %SubsMiss | 10861.366 |
| PAX | 9171.229 |
| S-Wing | 2168.852 |
| T/W-Ratio | 1176.909 |



## Direct Operating Costs

| Term | Orthog Estimate |
|---|---|
| PAX | -0.0025538 |
| %SubsMiss | 0.00177578 |
| Des-Range | 0.00075366 |
| S-Wing | 0.00017851 |
| T/W-Ratio | 0.00014310 |



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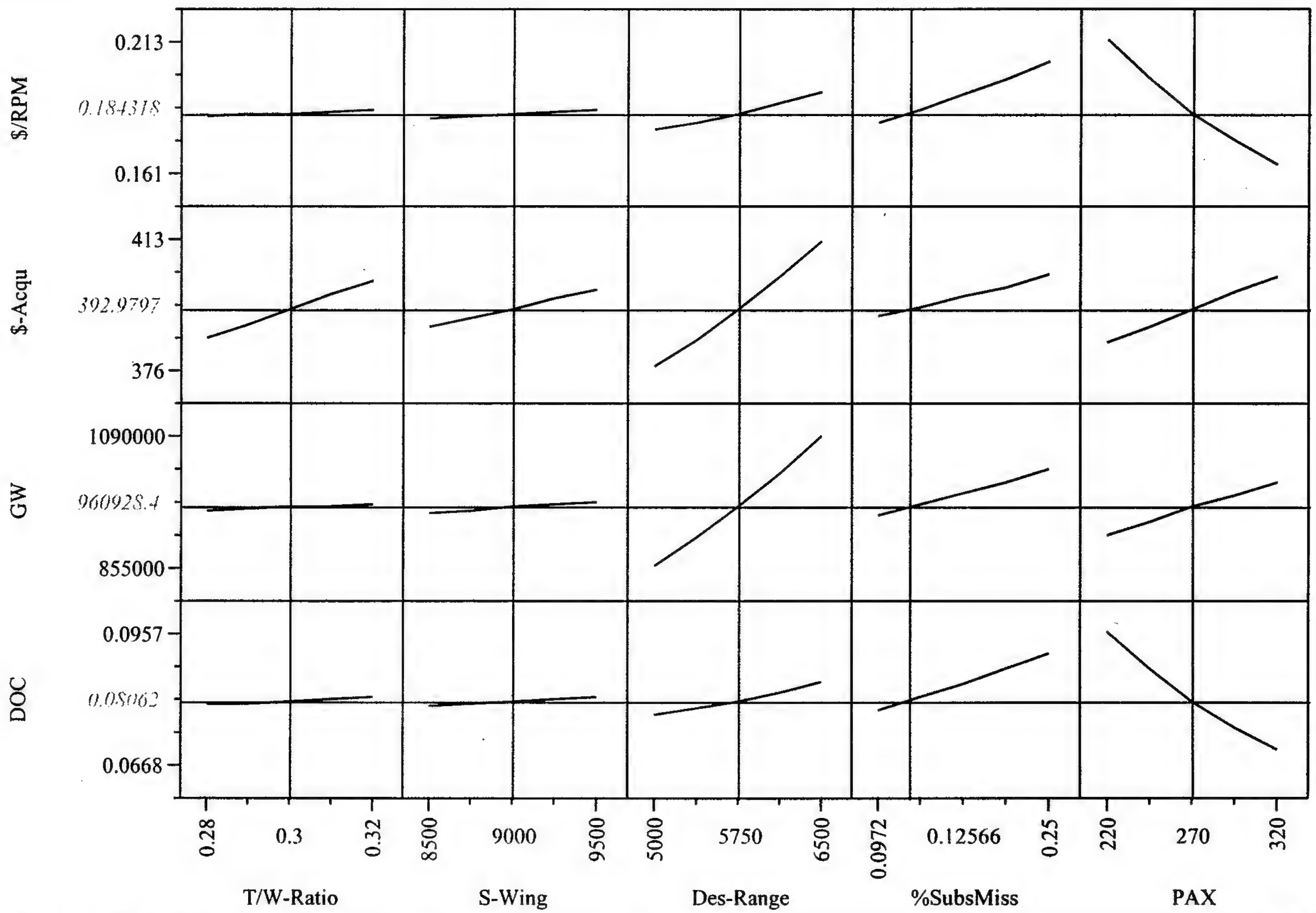
# Mission Requirements Sensitivities

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# Feasibility and Viability Assessment

- If design space is not technically feasible or economically viable, the decision maker has 3 options:

1) Open design variable ranges further

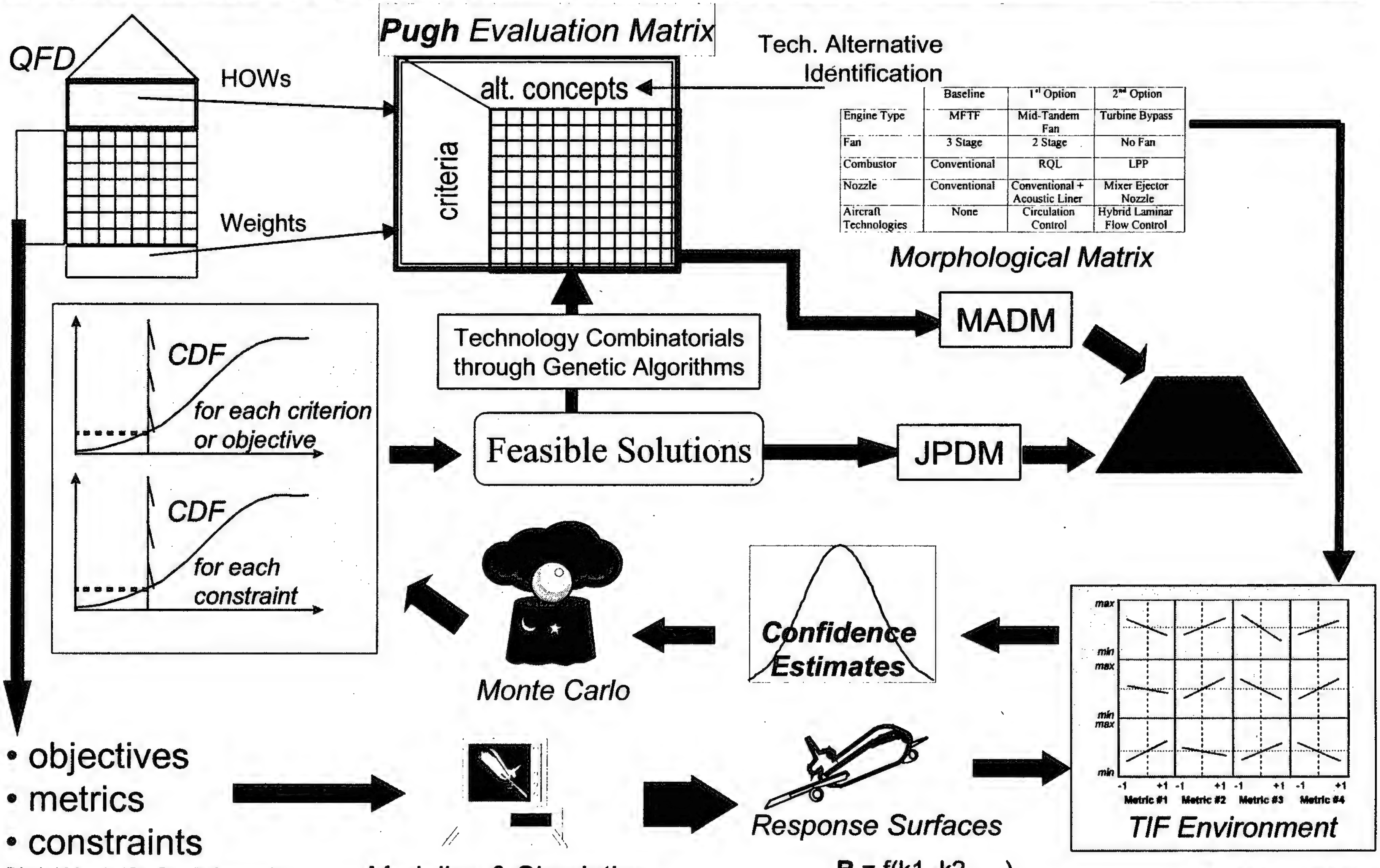
   *- Design Space Exploration yielded no improvement*

2) Relax constraints

   *- Non-negotiable in this case*

3) Infuse new technologies !!!

# Technology Identification Evaluation Selection (TIES)




| | Baseline | 1st Option | 2nd Option |
|---|---|---|---|
| Engine Type | MFTF | Mid-Tandem Fan | Turbine Bypass |
| Fan | 3 Stage | 2 Stage | No Fan |
| Combustor | Conventional | RQL | LPP |
| Nozzle | Conventional | Conventional + Acoustic Liner | Mixer Ejector Nozzle |
| Aircraft Technologies | None | Circulation Control | Hybrid Laminar Flow Control |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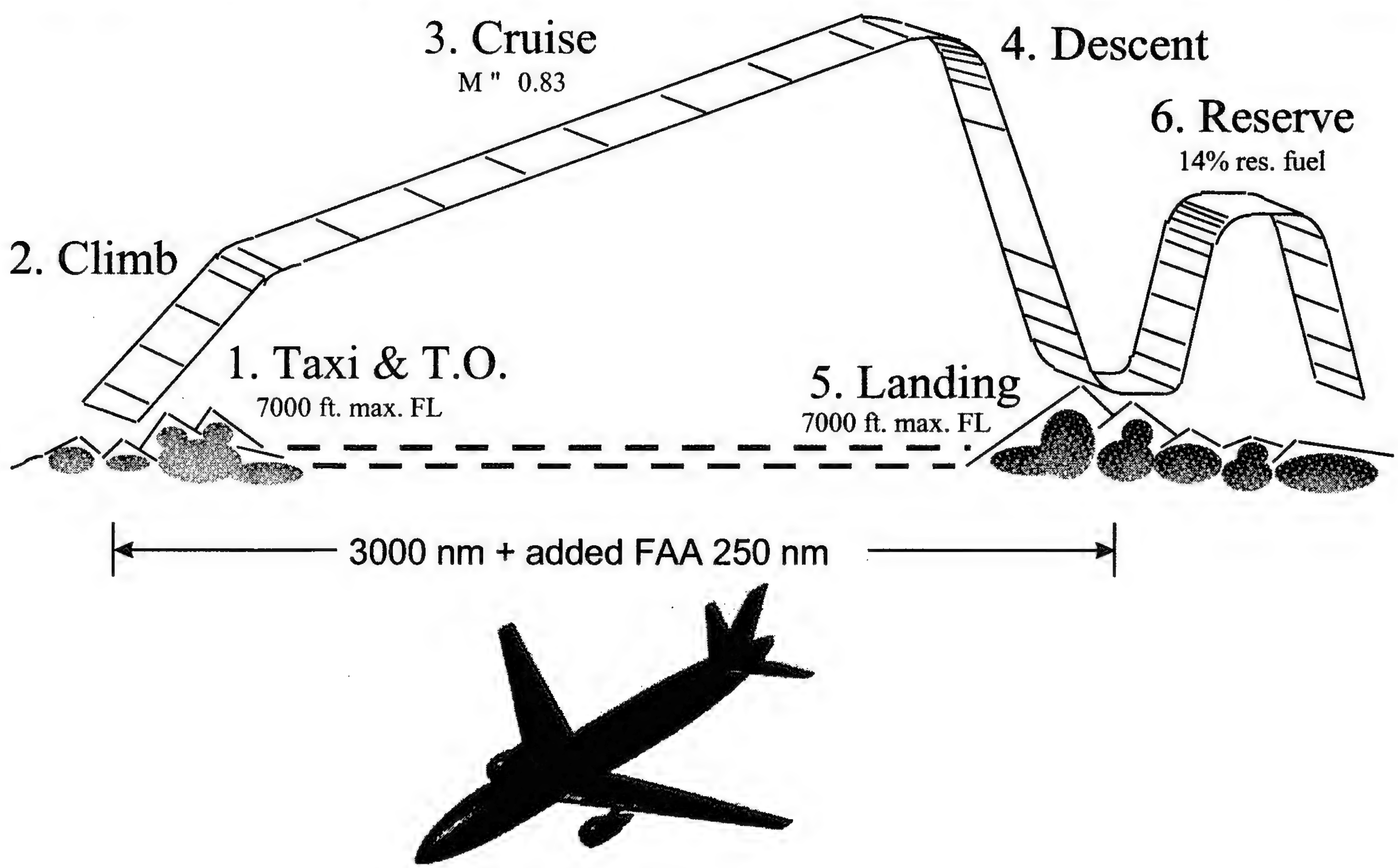
# Example Problem

- The implementation of the feasibility aspect of TIES has been performed on various vehicles
- The down-select of the specific technologies is the new dimension of the TIES method and will be applied for the example problem
- The proof of concept is performed on a 150 passenger, medium-range, intra-continental commercial transport and the technologies are evaluated deterministically
- See SAE Paper 98-5547 for the feasibility assessment, SAE Paper 98-5576 for the TIF, and AIAA 99-0183 for the joint probability decision making

# Problem Definition: *150 passenger concept*

## Medium Range, Intra-continental Commercial Vehicle





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# Problem Definition: *Quantitative System Level Metrics*

| Parameter | Baseline Value | Target | Target Value | Units |
|---|---|---|---|---|
| Weights and Performance | | | | |
| $V_{app}$ | 115.7 | *minimize* | ~ | kts |
| Fuel Burn | 44267 | -48% | 23019 | lbs |
| Landing FL | 4944 | -21% | 3906 | ft |
| OEW | 73850 | -40% | 44310 | lbs |
| TOFL | 5970 | -21% | 4706 | ft |
| TOGW | 149618 | -31% | 103236 | lbs |
| Economics | | | | |
| DOC+I | 5.22 | -42% | 3.03 | ¢/ASM |
| TAROC | 6.03 | -37% | 3.80 | ¢/ASM |

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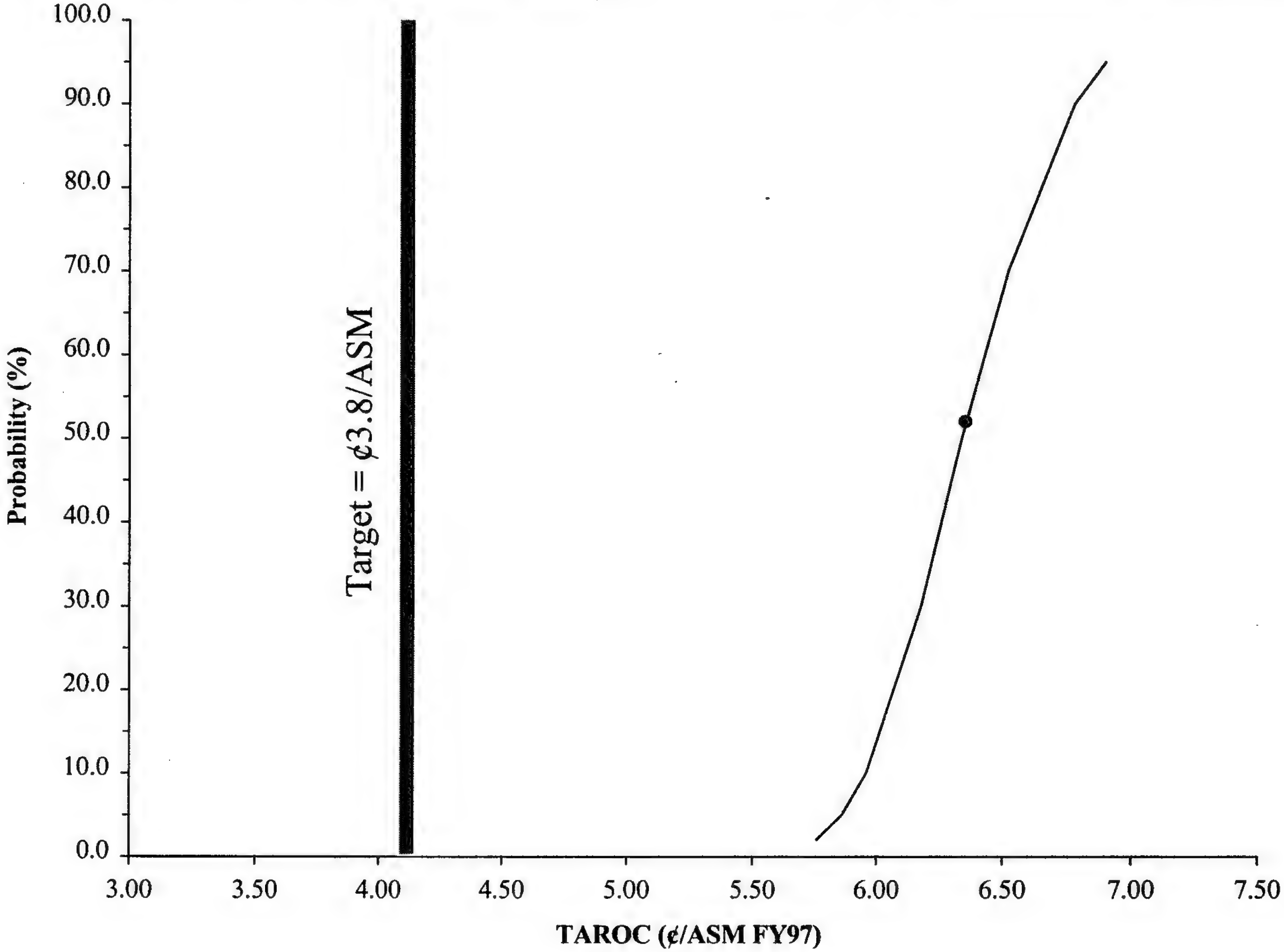
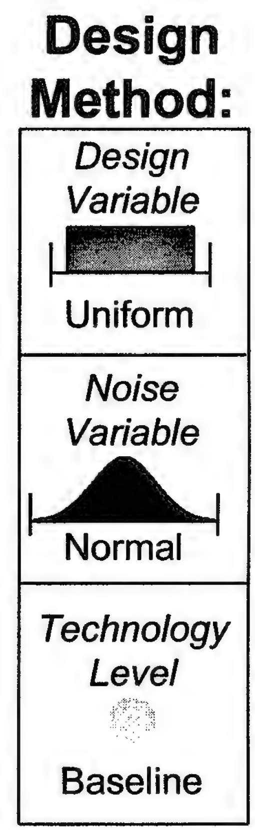
# Viability Assessment: *TAROC*



# Technology Identification

## *Compatibility Matrix*

**Compatibility Matrix**
**(1: compatible, 0: incompatible)**

| | Composite Wing | Composite Fuselage | Aircraft Morphing | Natural Laminar Flow Control | Maneuver Load Alleviation | AST Engine Concept | Integrally, Stiffened Aluminum Airframe Structures (wing) | HLFC | IHPTET Engines |
|---|---|---|---|---|---|---|---|---|---|
| Composite Wing | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| Composite Fuselage | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Aircraft Morphing | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Natural Laminar Flow Control | | | | 1 | 1 | 1 | 1 | 0 | 1 |
| Maneuver Load Alleviation | | | | | 1 | 1 | 1 | 1 | 1 |
| AST Engine Concept | | | | | | 1 | 1 | 1 | 0 |
| Integrally, Stiffened Aluminum Airframe Structures (wing) | | | | | | | 1 | 0 | 1 |
| HLFC | | | | | | | | 1 | 1 |
| IHPTET Engines | | | | | | | | | 1 |

Symmetric Matrix

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# Technology Identification

## *TIM: Technology Impact Matrix*

| Technical K_Factor Elements / Technical K_Factor Vector | Composite Wing | Composite Fuselage | Aircraft Morphing | Natural Laminar Flow Control | Maneuver Load Alleviation | AST Engine Concept | Integrally, Stiffened Aluminum Airframe Structures (wing) | HLFC | IHPTET Engines |
|---|---|---|---|---|---|---|---|---|---|
| Wing area | ~ | ~ | | ~ | +18% | ~ | ~ | ~ | ~ |
| Vertical tail area | ~ | ~ | ~ | ~ | -40% | ~ | ~ | ~ | ~ |
| Horizontal tail area | ~ | ~ | ~ | ~ | -36% | ~ | ~ | ~ | ~ |
| Drag | -2% | -2% | -3% | -5% | -3% | ~ | ~ | -10% | ~ |
| Subsonic fuel flow | ~ | -0.5% | -1.5% | ~ | ~ | -10% | ~ | +1% | -5% |
| Wing weight | -15% | ~ | -3% | ~ | ~ | ~ | -15% | +4% | ~ |
| Fuselage weight | ~ | -25% | -2% | ~ | ~ | ~ | ~ | ~ | ~ |
| Electrical weight | ~ | ~ | ~ | ~ | +5% | +3% | ~ | +2% | ~ |
| Engine weight | ~ | ~ | ~ | ~ | ~ | -30% | ~ | +0.5% | -20% |
| Hydraulics weight | ~ | ~ | ~ | ~ | -10% | ~ | ~ | ~ | ~ |
| AL wing structure manufacturing costs | ~ | ~ | ~ | ~ | ~ | ~ | -2.5% | ~ | ~ |
| O&S | +2% | +2% | ~ | ~ | ~ | -3% | -2% | +3% | -3% |
| RDT&E | +2% | +2% | +2% | +2% | +3% | -4% | ~ | +4% | +3% |
| Production costs | +10% | +10% | -3% | +1% | ~ | -3% | ~ | +1% | ~ |
| Utilization | -2% | -2% | ~ | ~ | ~ | +3% | +2% | -2% | +2% |

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# Technology Impact Matrix

- Potential system and subsystem level benefits and penalties associated with the technologies identified in the Morphological and Compatibility Matrices are established via expert questionnaires, physics-based modeling, or literature reviews
- In general, benefits and penalties are probabilistic (possibly stochastic) in nature
- Technology impact can be simulated in the TIF environment through technology "k_factor" vectors and summarized in a TIM

| "K" Factor Elements | Technical "K" Factor Vector | T1 | T2 | T3 |
|---|---|---|---|---|
| | k factor 1 | +4% | ~ | -10% |
| | k factor 2 | ~ | -3% | ~ |
| | k factor 3 | -1% | ~ | -2% |
| | k factor 4 | -2% | -2% | +3% |

where a technology can be represented as:

$$T_i = \vec{k}_i = \left\{ \begin{matrix} \mu_{i,1}, \sigma_{i,1} \\ \mu_{i,2}, \sigma_{i,2} \\ \cdots \\ \mu_{i,n}, \sigma_{i,n} \end{matrix} , TRL_i \right\}$$

where:
"i" : specific technology
"n": number of k_factors
"μ": mean of the k_factor
"σ": variance of the k_factor
"TRL": technology readiness level

# Technology Impact Forecasting

***"k" Factor RSE Generation***

| Technical Metric "K" Factor Elements | Non-dimensional impact Min (%) | Max (%) |
|---|---|---|
| Wing area | 0 | 18 |
| Vertical tail area | -40 | 0 |
| Horizontal tail area | -36 | 0 |
| Drag | -25 | 0 |
| Subsonic fuel flow | -17 | 1 |
| Wing weight | -33 | 4 |
| Fuselage weight | -27 | 0 |
| Electrical weight | 0 | 10 |
| Engine weight | -50 | 0.5 |
| Hydraulics weight | -10 | 0 |
| AL wing structure manufacturing costs | -2.5 | 0 |
| O&S | -8 | 7 |
| RDT&E | -4 | 18 |
| Production costs | -6 | 22 |
| Utilization | -6 | 7 |

Constraint/Objective = $f(k_1, k_2, \ldots, k_n)$ as obtained from a Design of Experiments to obtain a second order equation of the form:

$$R = b_o + \sum_{i=1}^{k} b_i k_i + \sum_{i=1}^{k} b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} k_i k_j$$

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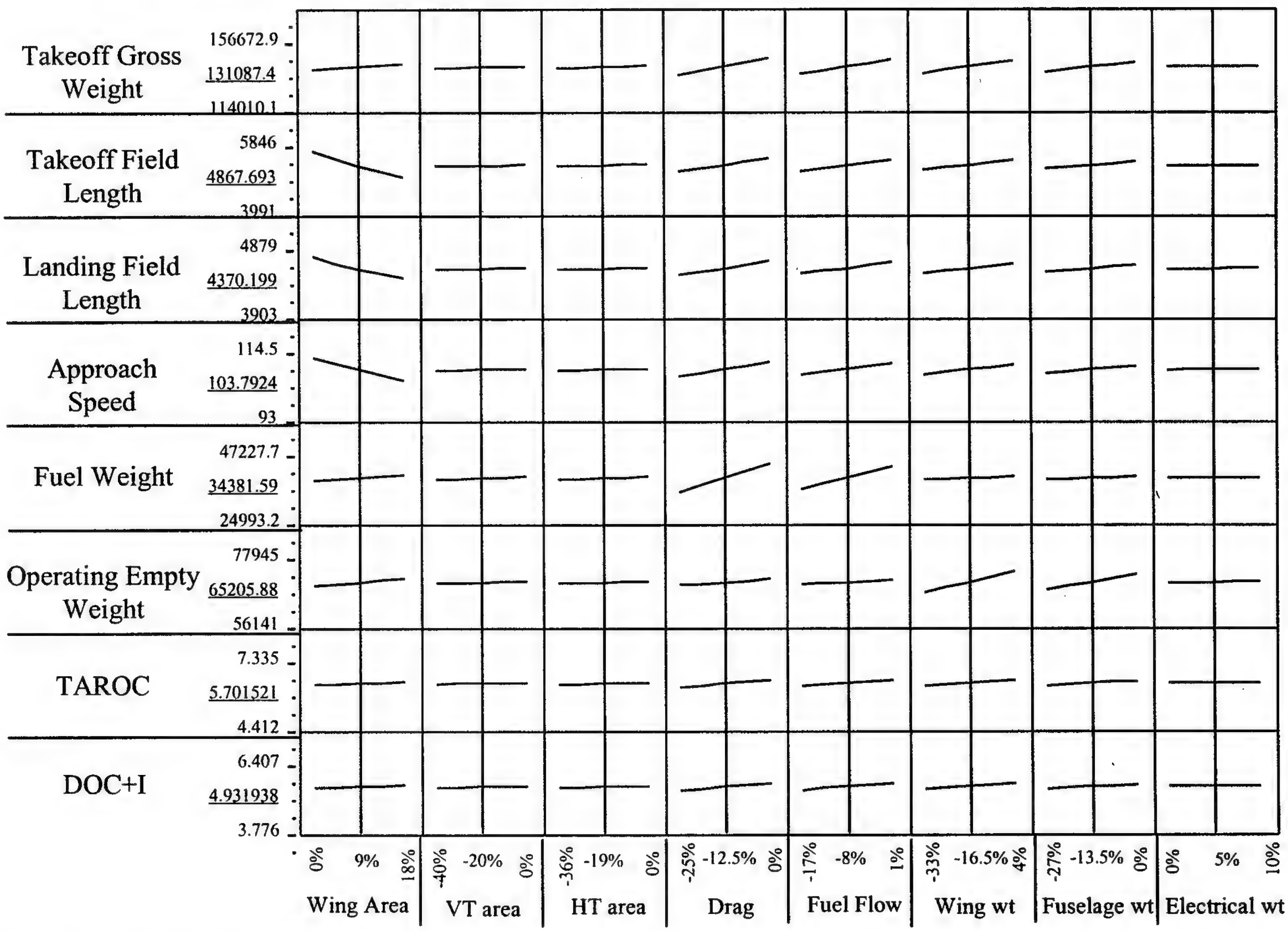
# TIF Environment (1)

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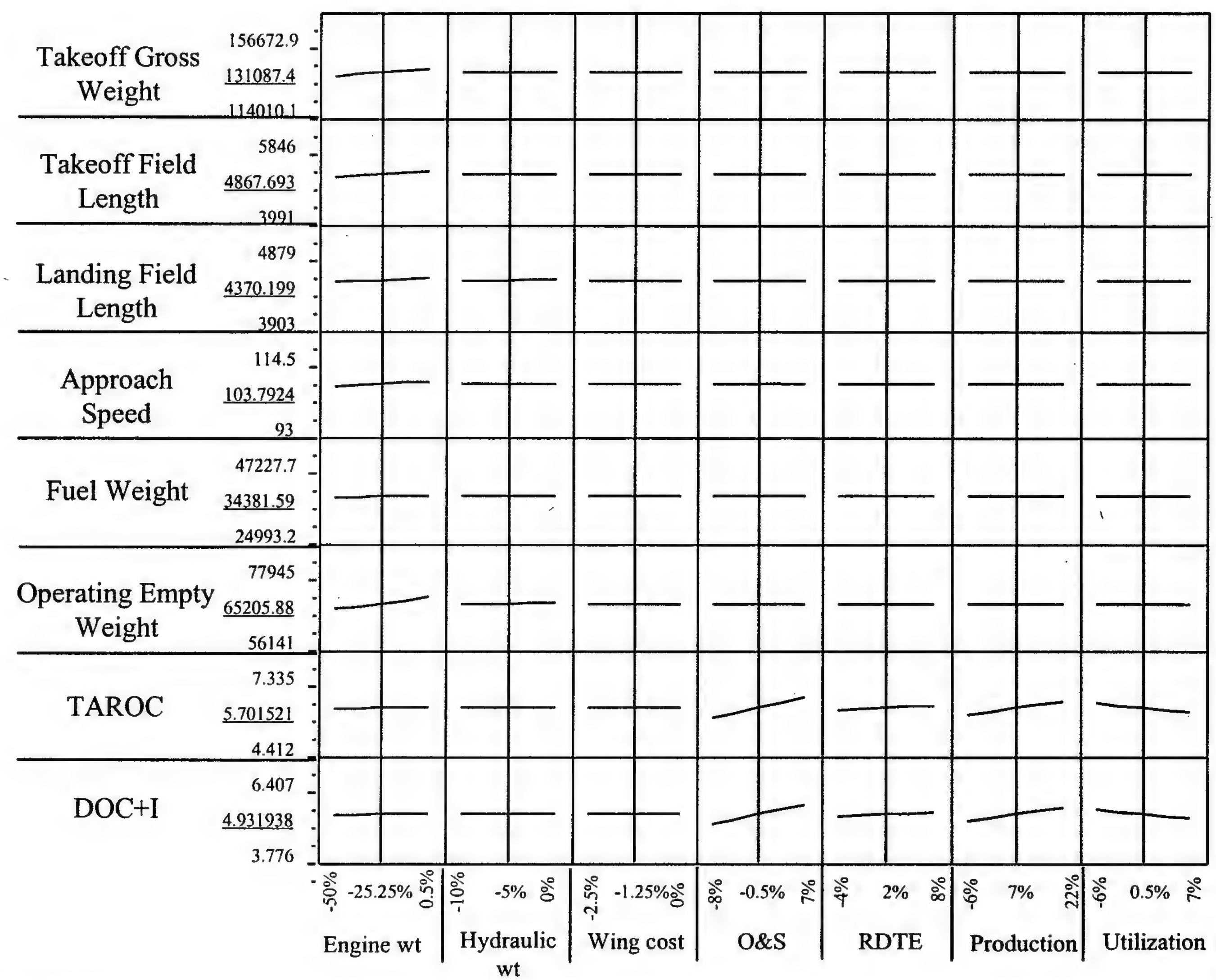
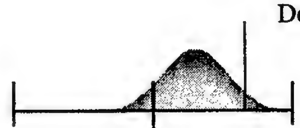
# TIF Environment (2)

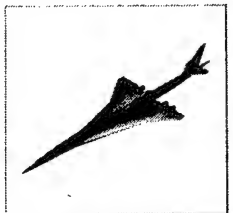


# Technology Mapping

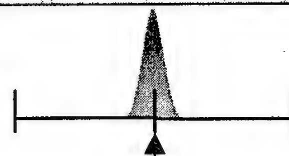
Infuse Tech #1 $\Rightarrow$ $f(\vec{k}_1)=\left\{\begin{matrix}\mu_{1,1},\sigma_{1,1} \\ \mu_{1,j},\sigma_{1,j},TRL=3 \\ \mu_{1,n},\sigma_{1,n}\end{matrix}\right\}$ $\xrightarrow{L/D}$




$\Rightarrow f\begin{pmatrix}disciplinary \\ metrics\end{pmatrix}_1 \Rightarrow \vec{A}_1=\left\{\begin{matrix}Performance_1 \\ Geometry \\ Economic_1\end{matrix}\right\}$

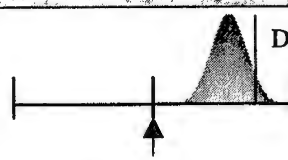


$f(\vec{k}_{conv})=\left\{\begin{matrix}\mu_{conv,1},\sigma_{conv,1} \\ \mu_{conv,j},\sigma_{conv,j},TRL=9 \\ \mu_{conv,n},\sigma_{conv,n}\end{matrix}\right\}$ $\xrightarrow{L/D}$

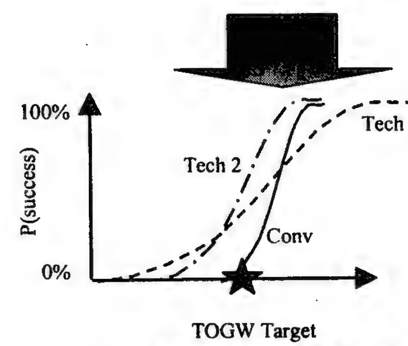



$\Rightarrow f\begin{pmatrix}disciplinary \\ metrics\end{pmatrix} \Rightarrow \vec{A}=\left\{\begin{matrix}Performance \\ Geometry \\ Economic\end{matrix}\right\}$

Infuse Tech #2 $\Rightarrow$ $f(\vec{k}_2)=\left\{\begin{matrix}\mu_{2,1},\sigma_{2,1} \\ \mu_{2,j},\sigma_{2,j},TRL=6 \\ \mu_{2,n},\sigma_{2,n}\end{matrix}\right\}$ $\xrightarrow{L/D}$




$\Rightarrow f\begin{pmatrix}disciplinary \\ metrics\end{pmatrix}_2 \Rightarrow \vec{A}_2=\left\{\begin{matrix}Performance_2 \\ Geometry \\ Economic_2\end{matrix}\right\}$

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# Technology Evaluation

- The identification of the proper mix of technologies for a given system is dominated by the curse of dimensionality
- *Curse of Dimensionality*: the search for the proper mix of technologies which will "best" satisfy the system level metrics or attributes can be enormous
  - $2^n$ combinations, where "n" is the number of technologies
    - 9 technologies implies 512 combinations
    - *20 technologies implies 1,048,576 combinations*
  - Computational expense of the analysis is the primary driver
    - *manageable*: full factorial investigation
    - *unmanageable*: genetic algorithm investigation

# Technology Evaluation: *Full Factorial Investigation*

| Case | T1 | T2 | T3 | ........ | T9 | Metric $_1$ | Metric $_2$ | ........ | Metric $_n$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | ........ | -1 | # | # | ........ | # |
| 2 | -1 | 1 | -1 | ........ | 1 | # | # | ........ | # |
| 3 | -1 | -1 | -1 | ........ | 1 | # | # | ........ | # |
| ⋮ | ⋮ | ⋮ | ⋮ | | ⋮ | ⋮ | ⋮ | | ⋮ |
| $2^n$ | 1 | 1 | 1 | ........ | 1 | # | # | ........ | # |

evaluations of Metric RSEs if all technologies are compatible

"1" implies technology applied
"-1" implies no technology

Metric value is determined from the RSEs

*Consider an alternative with aircraft morphing (T3) and IHPTET engines (T9)*

Recall:

$$\vec{k}_i = \begin{Bmatrix} k\_1 \\ k\_2 \\ k\_3 \\ k\_4 \\ k\_5 \\ k\_6 \\ k\_7 \\ k\_8 \\ k\_9 \\ k\_10 \\ k\_11 \\ k\_12 \\ k\_13 \\ k\_14 \\ k\_15 \end{Bmatrix}$$

**Alternative with: T3**

$$\vec{k}_3 = \begin{Bmatrix} \sim \\ \sim \\ \sim \\ -3\% \\ -1.5\% \\ -3\% \\ -2\% \\ \sim \\ \sim \\ \sim \\ \sim \\ \sim \\ +2\% \\ -3\% \\ \sim \end{Bmatrix}$$

**Alternative with: T9**

$$\vec{k}_9 = \begin{Bmatrix} \sim \\ \sim \\ \sim \\ \sim \\ -5\% \\ \sim \\ \sim \\ \sim \\ -20\% \\ \sim \\ \sim \\ -3\% \\ +3\% \\ \sim \\ +2\% \end{Bmatrix}$$

**Alternative with: T3+T9**

$$\vec{k}_{3+9} = \begin{Bmatrix} \sim \\ \sim \\ \sim \\ -3\% \\ -6.5\% \\ -3\% \\ -2\% \\ \sim \\ -20\% \\ \sim \\ \sim \\ -3\% \\ +5\% \\ -3\% \\ +2\% \end{Bmatrix}$$

Metric RSE = $f(\vec{k}_{3+9})$

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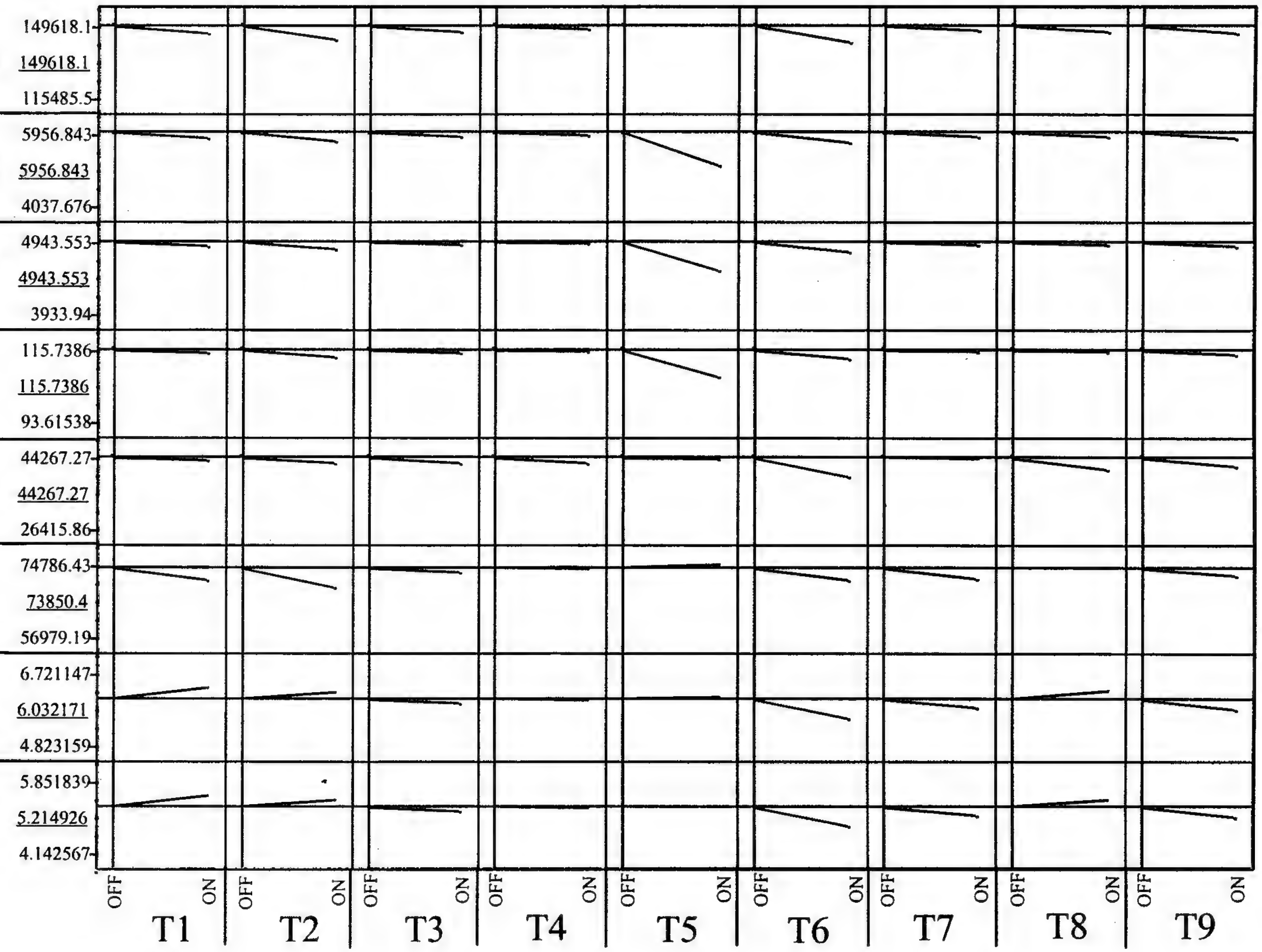
# Full Factorial Technology Evaluation




**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines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# Technology Resource Allocation

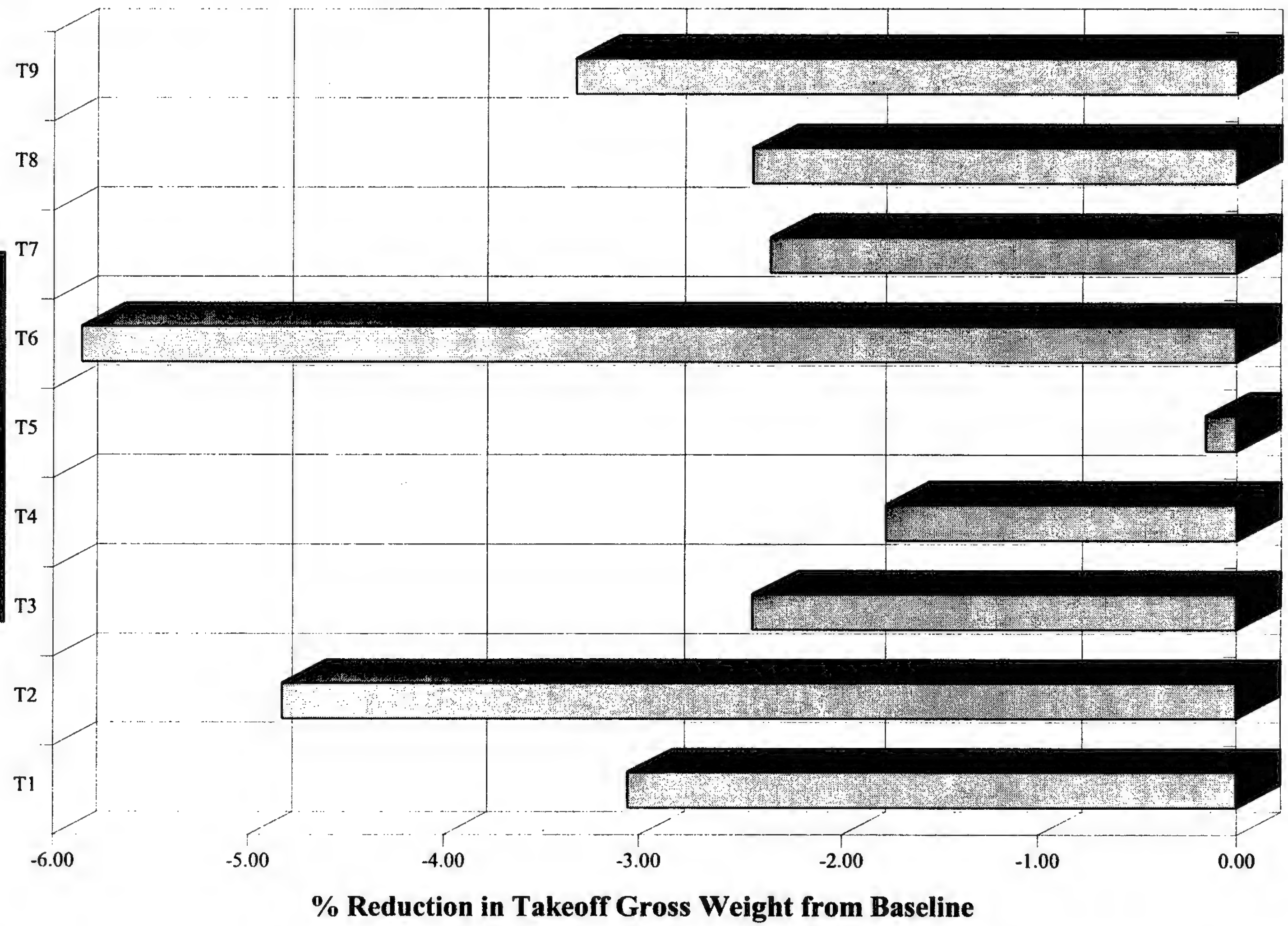
- Based on the TIES method results, the most influential individual technologies can be compared to the baseline metrics in an efficient and rapid manner

- The most influential technologies can be identified so as to optimize program resource allocation for technology research and development to overcome constraints or meet objectives

# Technology Resource Allocation

## *TOGW*

**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines

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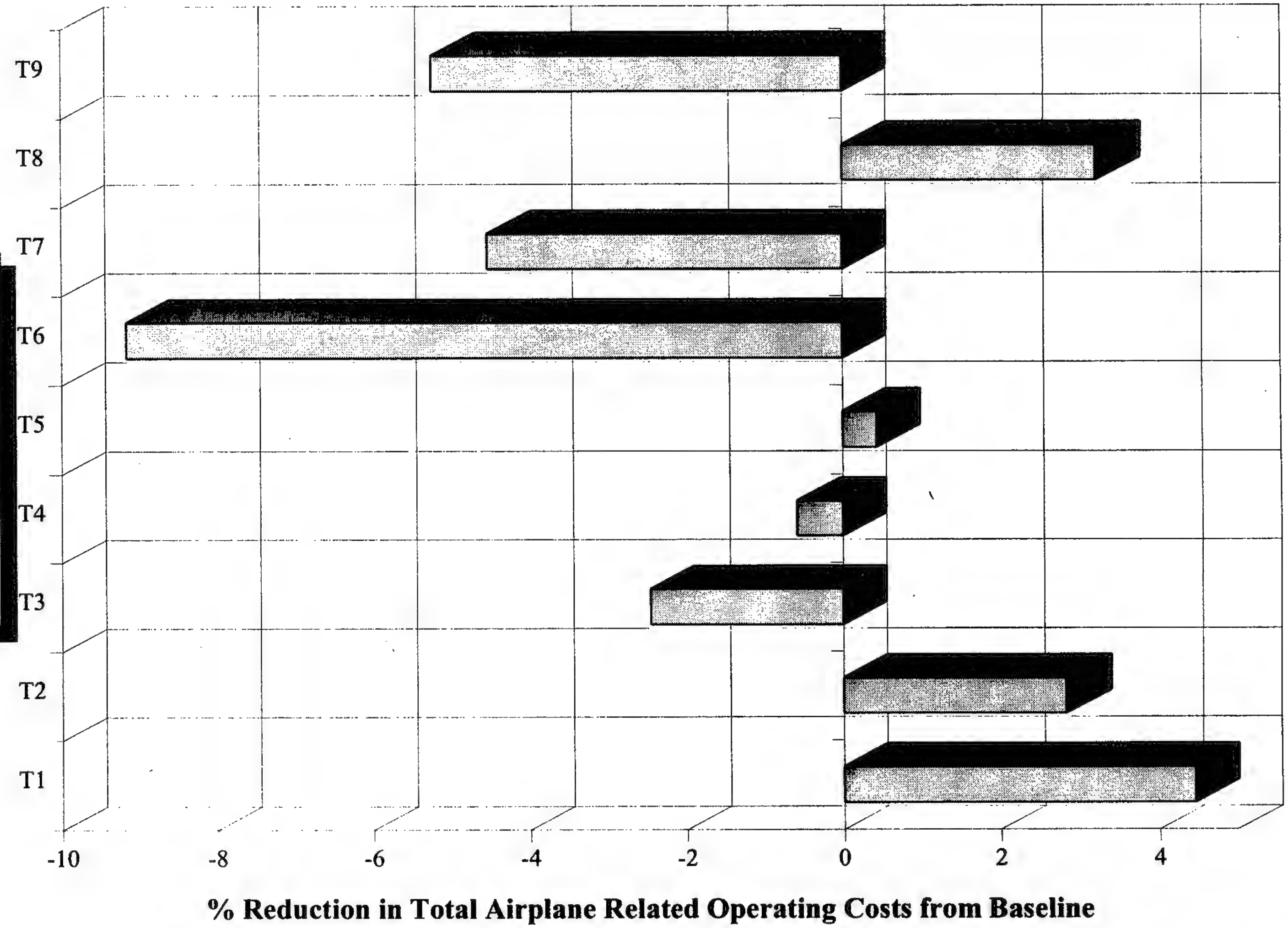
# Technology Resource Allocation

## *TAROC*

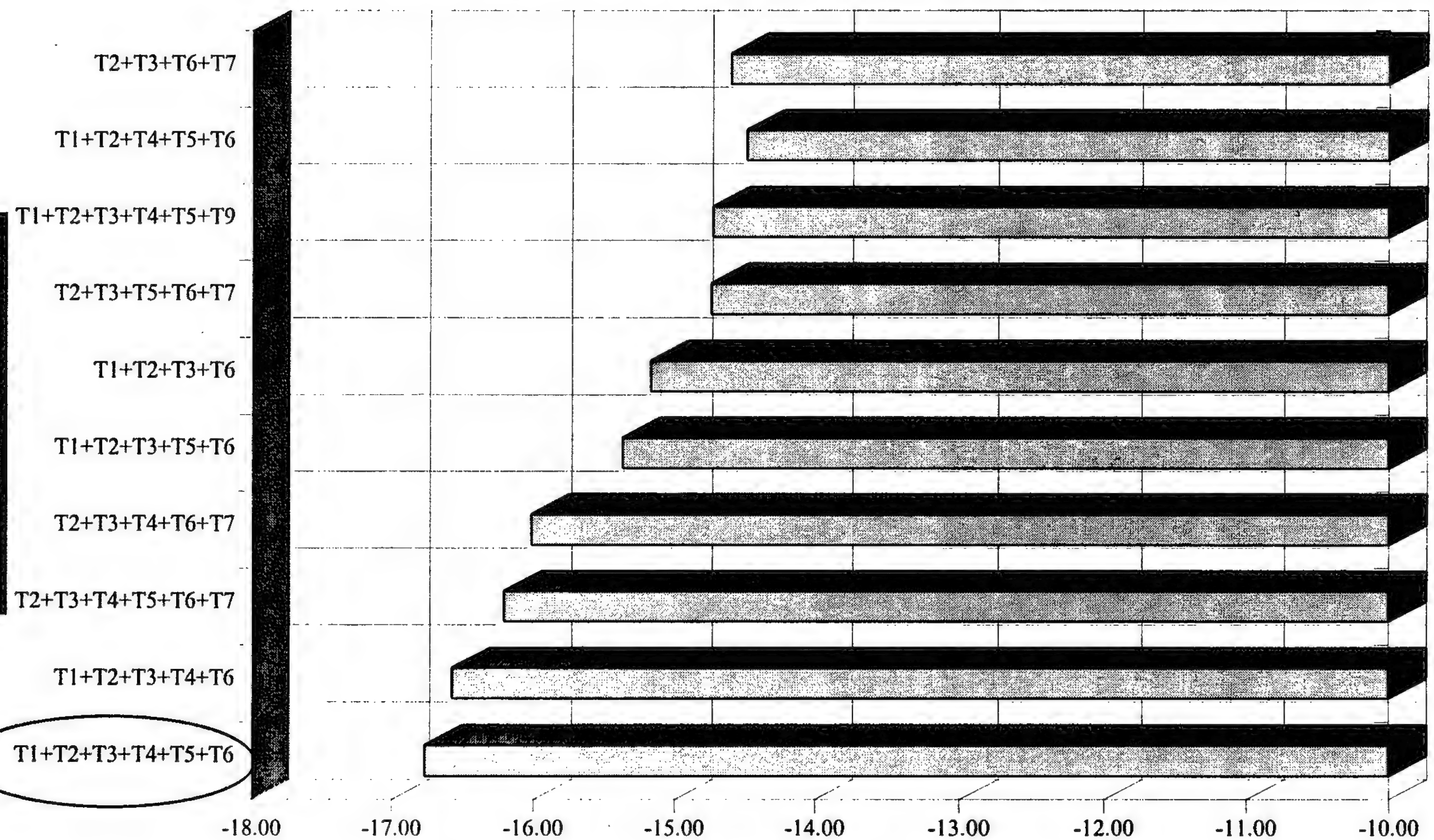
**Technologies:**
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines



# Top Alternatives

## *Evaluation Based on Minimum TOGW*

**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines

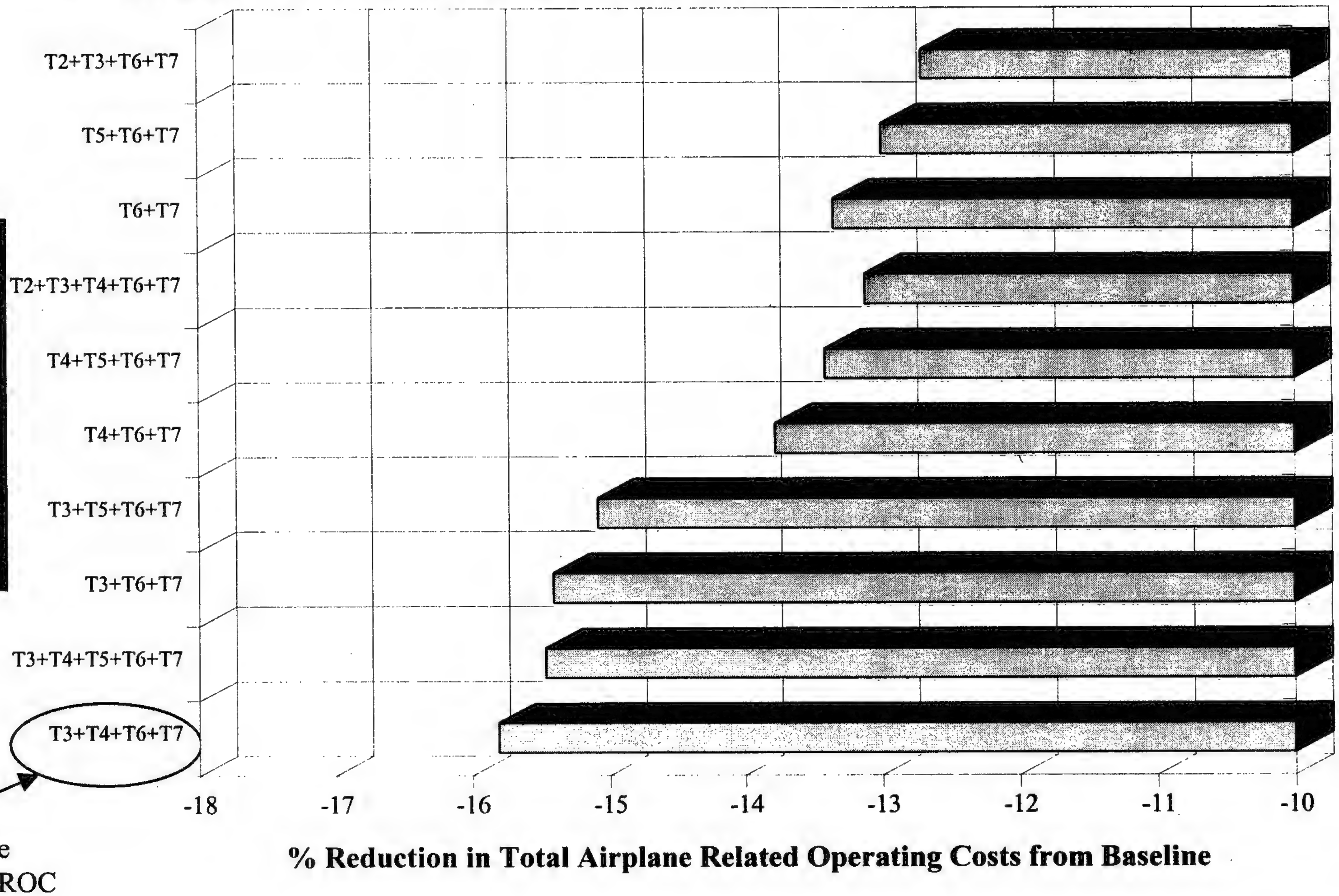



"Best" Alternative
for Minimum TOGW

# Top Alternatives

## *Evaluation Based on Minimum TAROC*

**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines

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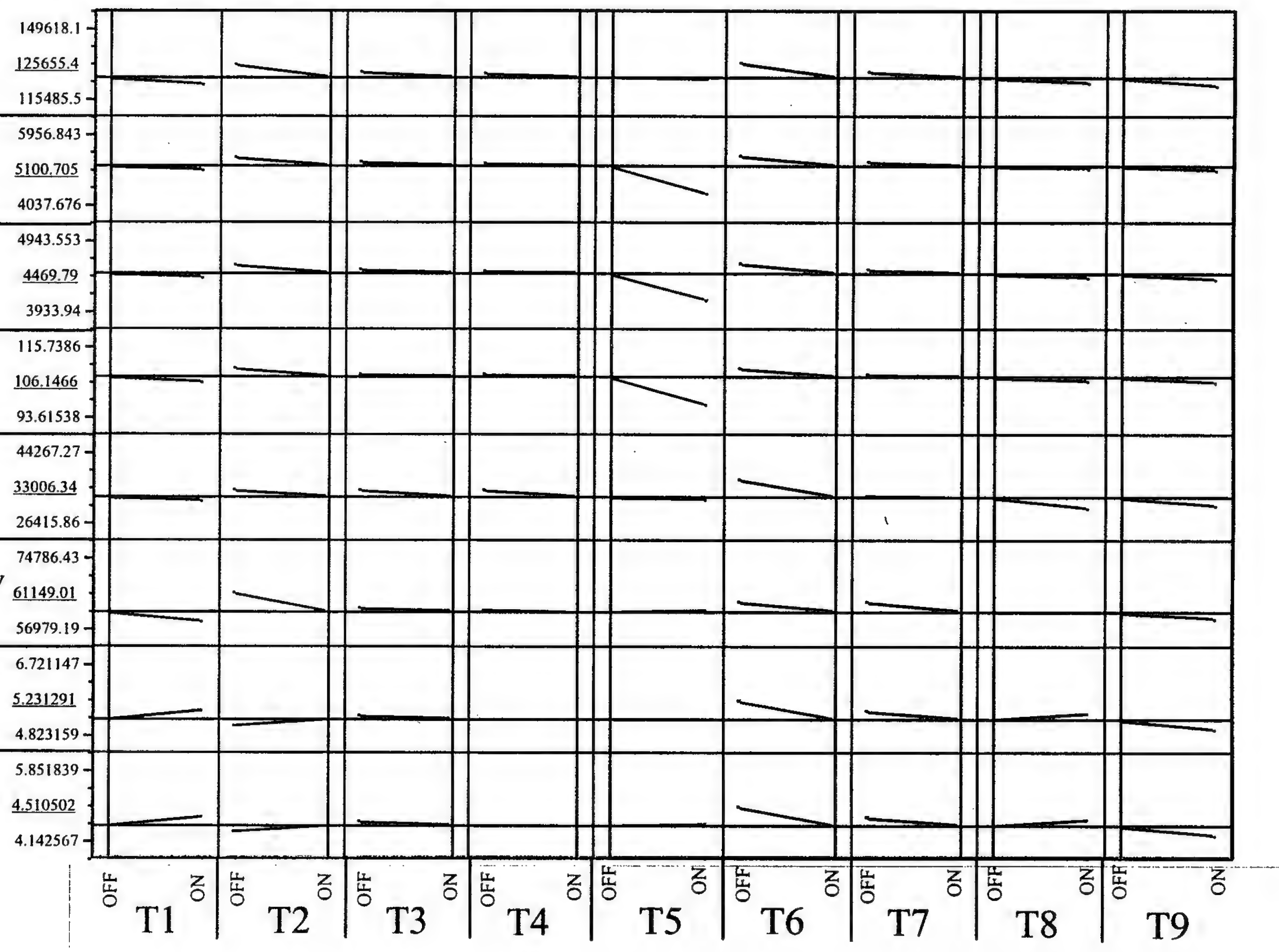
# "Best" Alternative

***Evaluation Based on Minimum TAROC and TOGW***




**Technologies**:
T1: Composite Wing
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T3: Aircraft Morphing
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T9: IHPTET Engines

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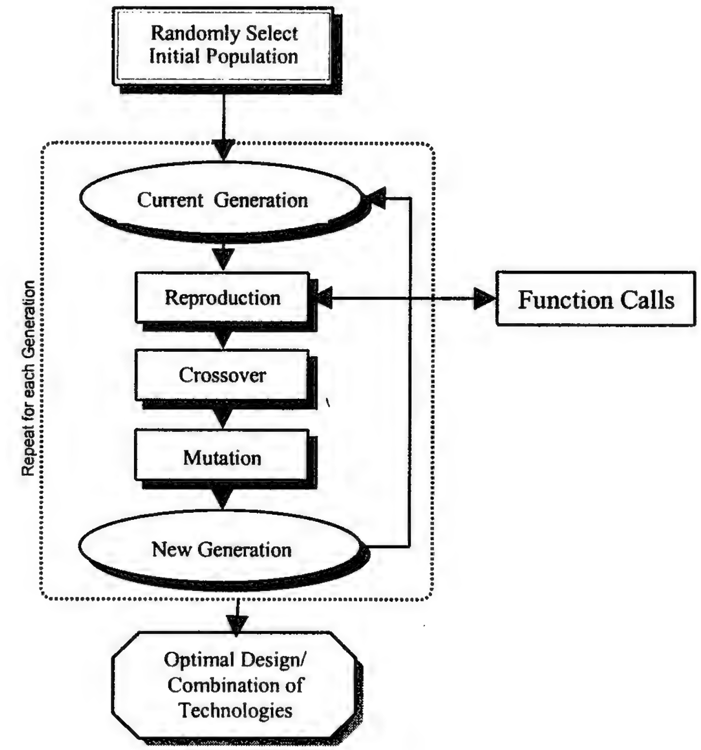
# Genetic Algorithm Investigation

- A simple deterministic proof of concept was performed with a genetic algorithm (GA) for the equal weighting OEC
- The identical mix of technologies from the TOPSIS technique was obtained
- Future work will focus on application of the GA method with probabilistic k_factor vectors and multi-attribute and conflicting objectives

# Genetic Algorithm Implementation

- Identify:
  - Number of Technologies
  - Number of Subsystems
  - Number of Metric Responses
- Specify/Provide:
  - Technology Impact Matrix (TIM)
  - Compatibility Matrix
  - Computation Metamodels for Metric Response
  - Multi-Attribute Decision Making Strategy
- GA yields:
  - best combination of technologies based on identified measures and provided information

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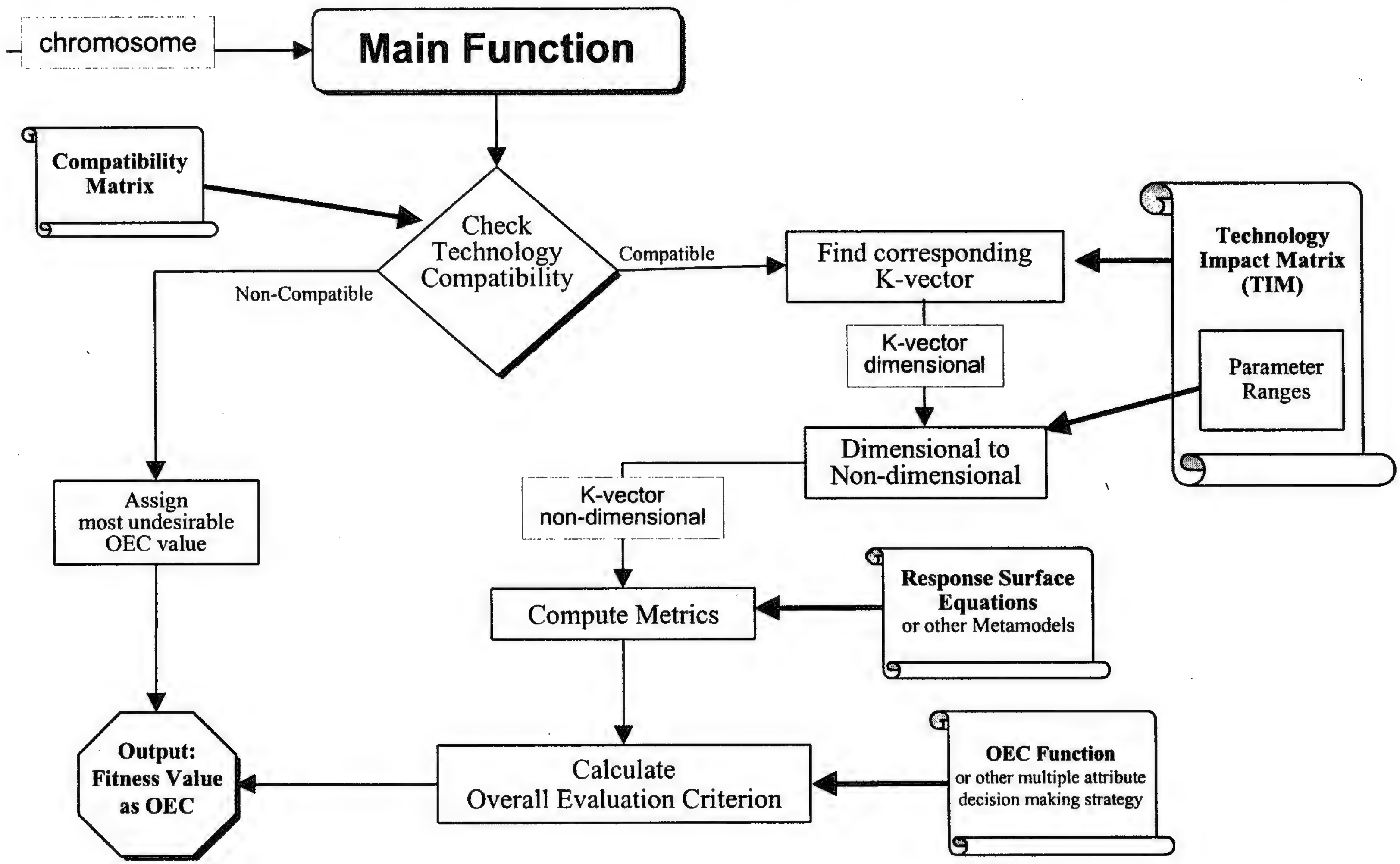
# Genetic Algorithm Function Calls

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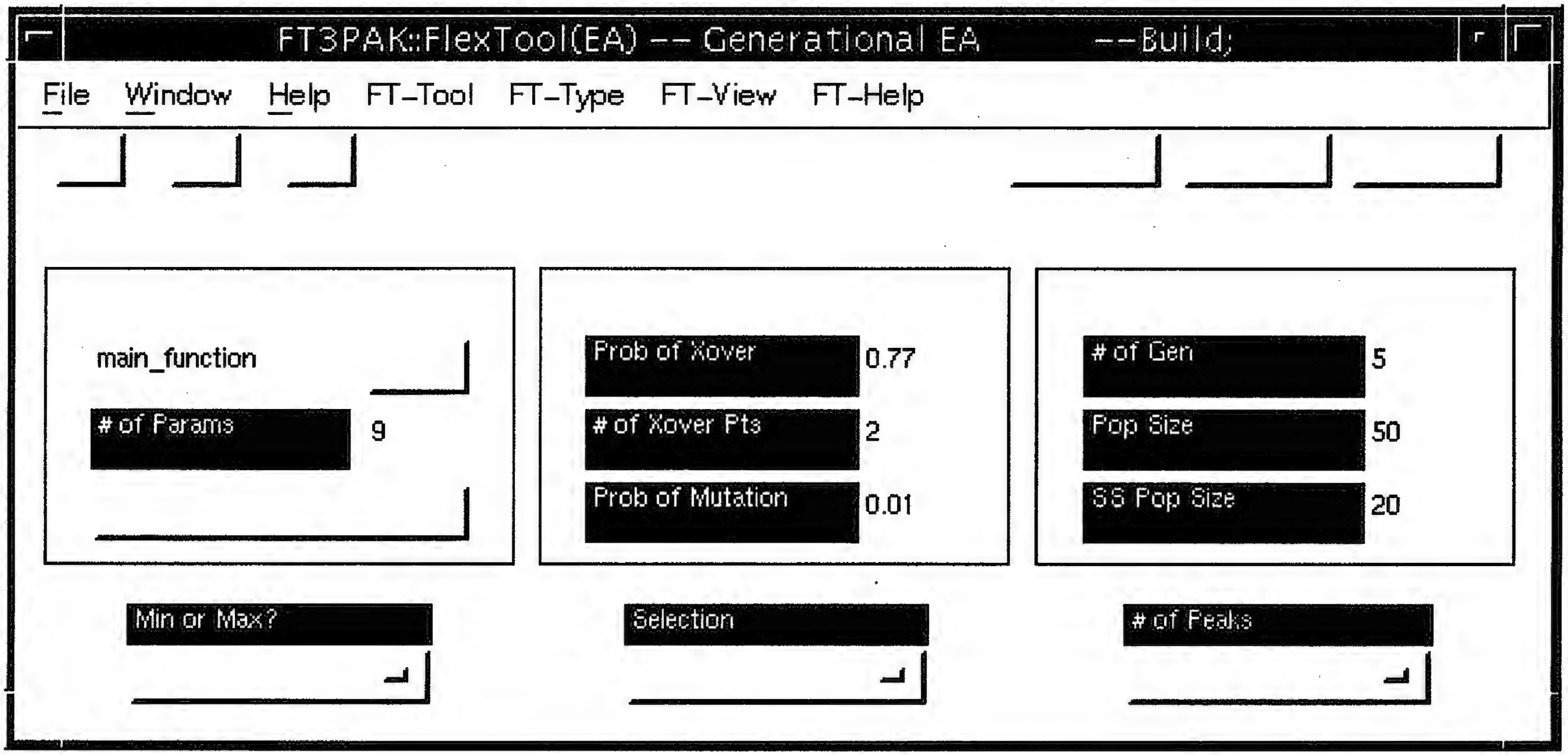
# Specification of GA parameters



# Conclusions

- A methodology for the systematic down-select of the proper mix of technologies which satisfies the imposed system level metrics was established
- Method could be interpreted for resource allocation of various technologies
- Future work will focus on:
  - probabilistic and stochastic evaluation
  - multi-attribute decision making with conflicting objectives
  - more technology combinations for GA implementation
  - other vehicle concepts

# Multi Criteria Decision Making Technique for Systems Design: Joint Probabilistic Decision Making (JPDM)

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# Hypothesis: Multi Criteria Motivation

- Customer needs translate to system characteristics called attributes or constraints which become decision criteria for product selection.
- Complex systems have a multitude of attributes, such as life cycle cost, gross weight, excess power, safety, dependability, etc.
- Decisions based on one criterion/attribute may yield products with poor performance in other attributes.

A design method is needed that accounts for all criteria concurrently.

# Hypothesis: Probabilistic Motivation

- Most assumptions made about the operational environment of the system are uncertain.

➡ Deterministic assumptions misrepresent the actual behavior/knowledge.

- Computer model fidelity introduces uncertainty in the output prediction.
- Use of new technologies adds uncertainty due to readiness/availability.

➡ A probabilistic formulation of the design process is needed to capture and analyze uncertainties.

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# Typical Design Questions

- How to compare different design solutions with multiple objectives on an equal basis.
- How to compare different design solutions despite uncertainty about relevance and accuracy of design assumptions.
- How to trade one requirement for another.
- How to determine optimal solutions based on multiple objectives.

# Shortcomings of Existing Decision Aids

Current multi criteria approaches determine either just the best solution of a small finite set based on many criteria, called Multi Attribute Decision Making (MADM), or the best solution of an infinite set based on just a few criteria, called Multi Objective Decision Making (MODM).

| | | Alternatives | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | ..... | Alt N |
| Criteria | Crit 1 | Value | Value | Value | Value | Value | | Value |
| | Crit 2 | Value | Value | Value | Value | Value | | Value |
| | Crit 3 | Value | Value | Value | Value | Value | | Value |
| | Crit 4 | Value | Value | Value | Value | Value | | Value |
| | Crit 5 | Value | Value | Value | Value | Value | | Value |
| | ..... | | | | | | | |
| | Crit M | Value | Value | Value | Value | Value | | Value |

MADM
MODM
JPDM

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# Proposed Method

## Joint Probabilistic Decision Making (JPDM)

- Combines advantages of probabilistic treatment of uncertain information with multi criteria decision making.
- Determines the probability of satisfying all (specified) customer needs/criteria values as an objective function within TIES.
- Facilitates visual trade-offs for two requirements at a time.

# Four Steps for Implementing JPDM

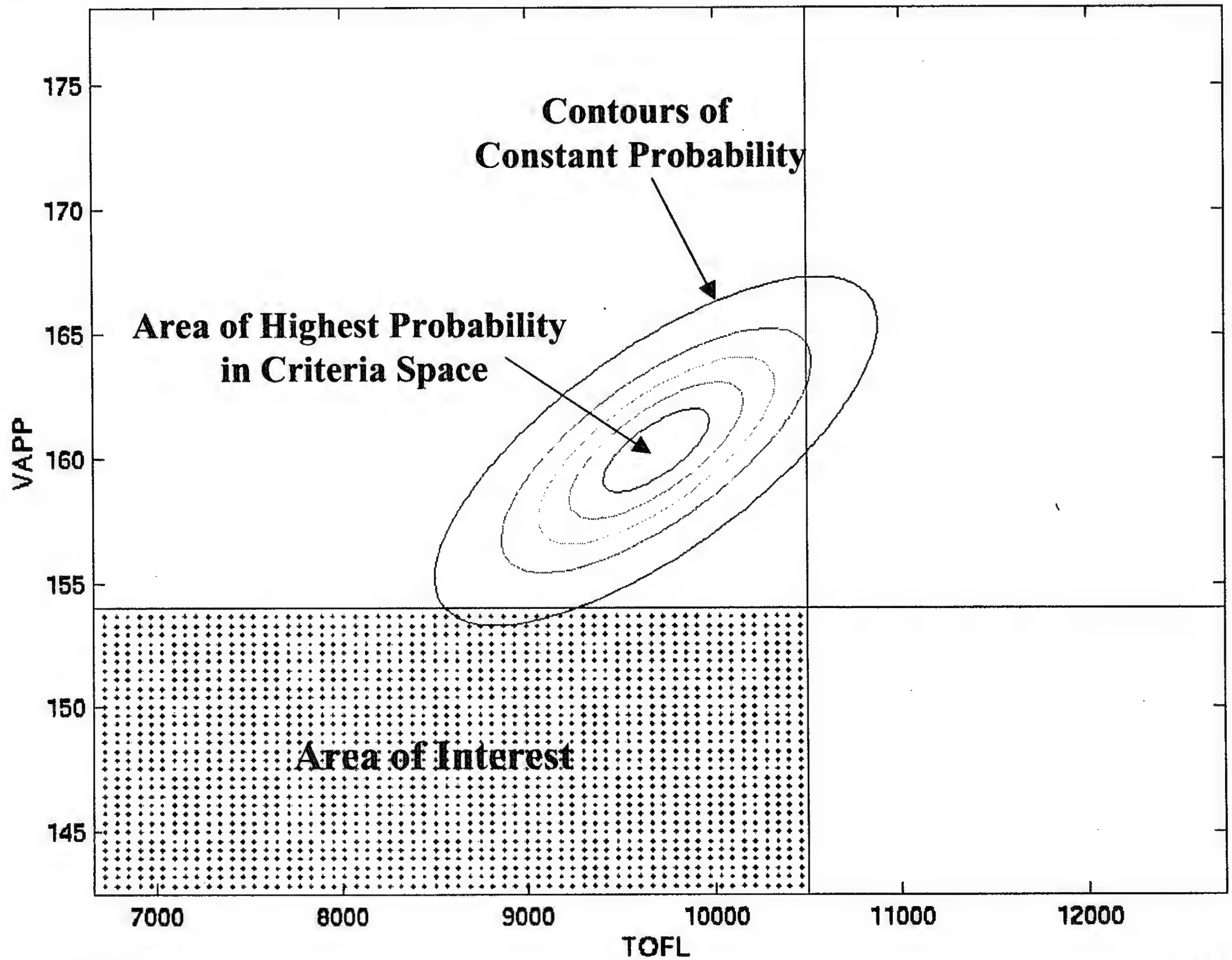
**Step 1:** Determine objectives/requirements of customer and designer.

**Step 2:** Assign probability distributions to design assumptions (fix design/control variables).

**Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.

**Step 4:** Determine solution with highest joint probability (two problems: MADM or MODM).

# Joint Probability Density Function - 2D

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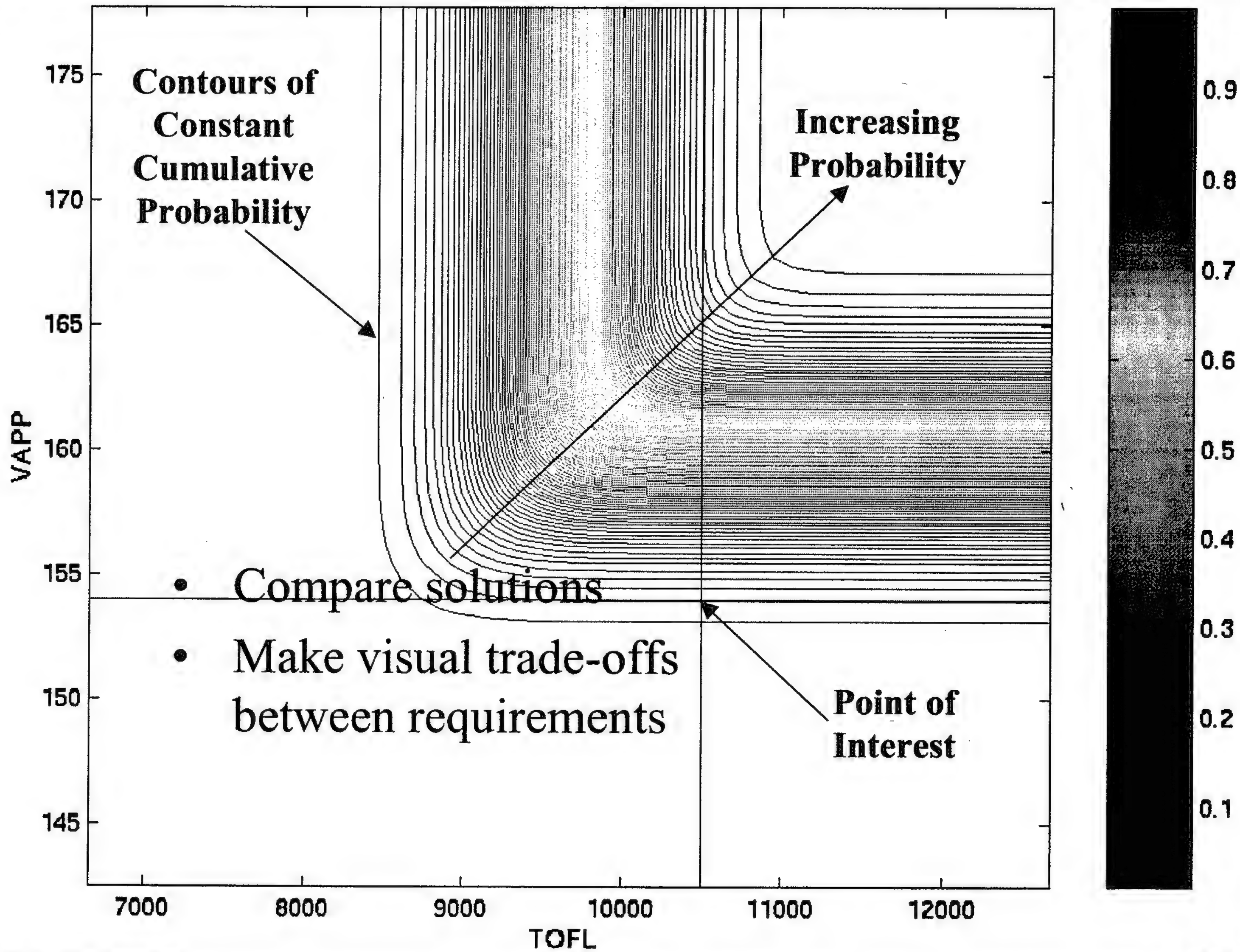
# Joint Cumulative Distribution Function - 2D




- Compare solutions
- Make visual trade-offs between requirements

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# Implementation (cont'd)

**Step 1:** Determine objectives/requirements of customer and designer.

**Step 2:** Assign probability distributions to design assumptions (fix design/control variables).

**Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.

**Step 4:** Determine solution with highest joint probability (two problems: MADM or MODM).

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# Empirical Distribution Function (EDF)

- Estimates probability of occurrence of a specified event based on sample events.
- Counts how many times the event occurred in the sample.
- Denoted for one variable and sample $x_i$, i=1 to n by

Density function: $$f_X(a) = \frac{1}{n}\sum_{i=1}^{n} I(x_i = a) \qquad I(x_i = a) = \begin{cases} 1 \text{ if true} \\ 0 \text{ if false} \end{cases}$$

Cumulative function: $$F_X(a) = \frac{1}{n}\sum_{i=1}^{n} I(x_i \le a) \qquad I(x_i \le a) = \begin{cases} 1 \text{ if true} \\ 0 \text{ if false} \end{cases}$$

- Joint cumulative formulation, sample $(x_i, y_i, z_i)$, i=1 to n:

$$F_{XYZ}(a,b,c) = \frac{1}{n}\sum_{i=1}^{n} I(x_i \le a, y_i \le b, z_i \le c)$$

# EDF - Advantages/Disadvantages

- Advantages:
  - Most exact method
  - Does not need approximation with standard distributions
  - Estimates joint probability from data directly

- Disadvantages:
  - Needs large amount of data to be accurate
  - Requires modeling and simulation
  - Availability of data in conceptual and preliminary design may be limited or too expensive
  - Joint probability estimation itself is more time consuming

# Joint Probability Model (JPM)

- Analytical model to estimate multivariate joint probability.
- Uses statistics of marginal distributions (mean $\mu$ and standard deviation $\sigma$).
- Uses correlation coefficients of criteria.
- Allows continued use of techniques that estimate marginal distributions.
- Example for bivariate normal model:

$$f_{XY}(a,b) = \frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2}} \exp\{\frac{1}{2\rho^2-2}[(\frac{a-\mu_X}{\sigma_X})^2 - 2\rho(\frac{a-\mu_X}{\sigma_X})(\frac{b-\mu_Y}{\sigma_Y}) + (\frac{b-\mu_Y}{\sigma_Y})^2]\}$$

- Formulation for n-variate normal model:

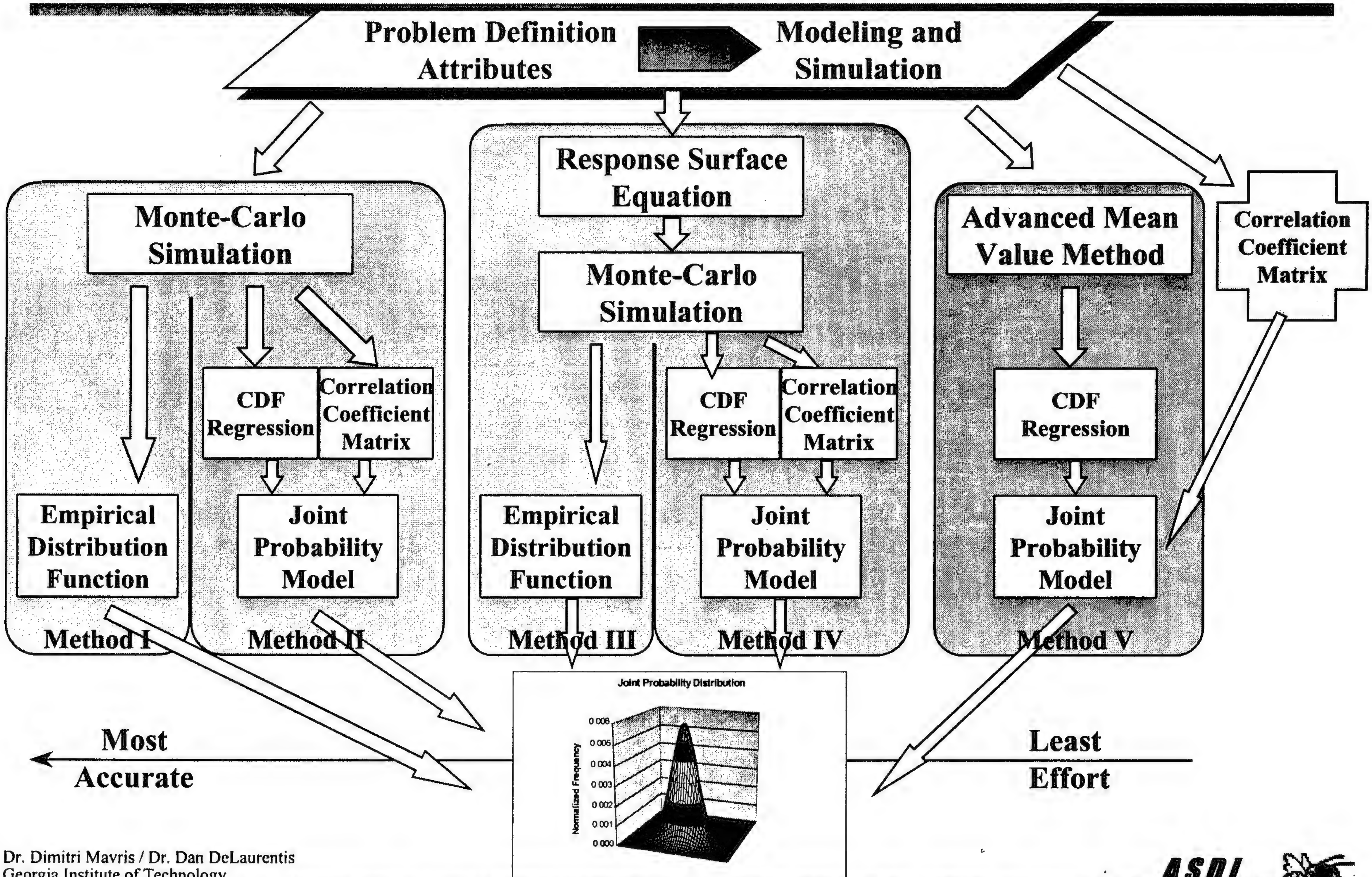
$$f(\mathbf{x};\boldsymbol{\mu},\boldsymbol{\Sigma}) = \frac{1}{(2\pi)^{n/2}|\boldsymbol{\Sigma}|^{1/2}} e^{-Q_n(\mathbf{x};\boldsymbol{\mu},\boldsymbol{\Sigma})/2}, \quad Q_n(\mathbf{x};\boldsymbol{\mu},\boldsymbol{\Sigma}) = (\mathbf{x}-\boldsymbol{\mu})'\boldsymbol{\Sigma}^{-1}(\mathbf{x}-\boldsymbol{\mu}),$$

$$\mathbf{x} \in \Re^n \quad \Sigma = \text{Correlation Coefficient Matrix}$$

# JPM - Advantages/Disadvantages

- Advantages:
  - Needs limited information for execution
  - Can employ expert guesses in case of lack of simulation
  - Fast evaluation of joint probability
  - Method can be used in conceptual or preliminary design
- Disadvantages:
  - Requires approximation of actual data by standard distribution
  - Requires correlation coefficient, which may not be available in early stages of design

# Step 3 - Exeuction Accuracy Vs. Efficiency

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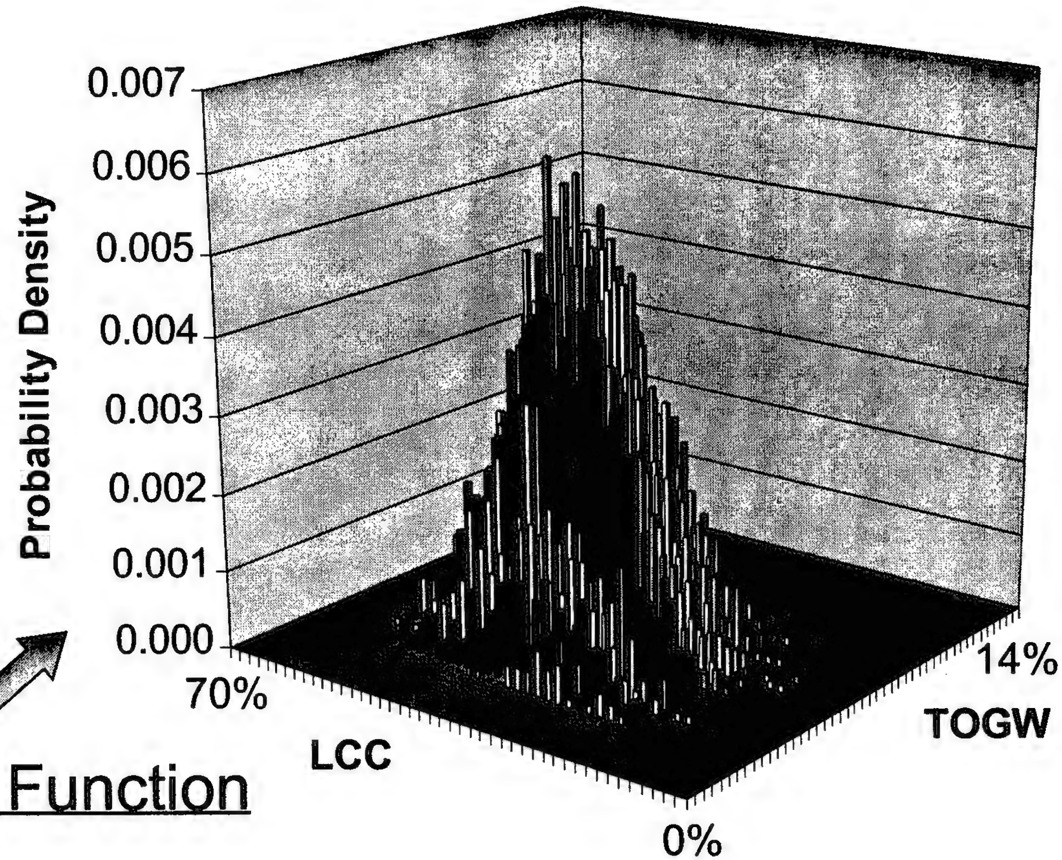
# Results - Method I

## Monte Carlo Simulation

10,000 samples

| LCC | TOGW |
|---|---|
| 10.5% | 2.3% |
| 5.3% | 1.2% |
| 43.8% | 12.5% |
| • | • |
| • | • |
| • | • |

**Joint Probability Distribution**




## Empirical Distribution Function

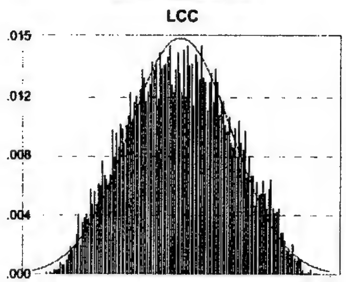
$$f(LCC, TOGW) = \frac{1}{10,000} \sum_{i=1}^{10,000} I(LCC - \varepsilon < lcc_i \leq LCC + \varepsilon, TOGW - \varepsilon < togw_i \leq TOGW + \varepsilon)$$

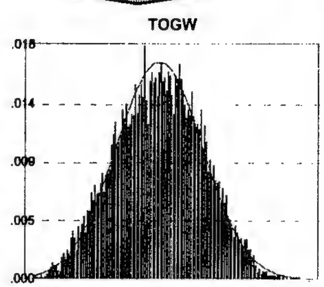
# Results - Method II

## Monte Carlo Simulation

10,000 samples

| LCC | TOGW |
|---|---|
| 10.5% | 2.3% |
| 5.3% | 1.2% |
| 43.8% | 12.5% |

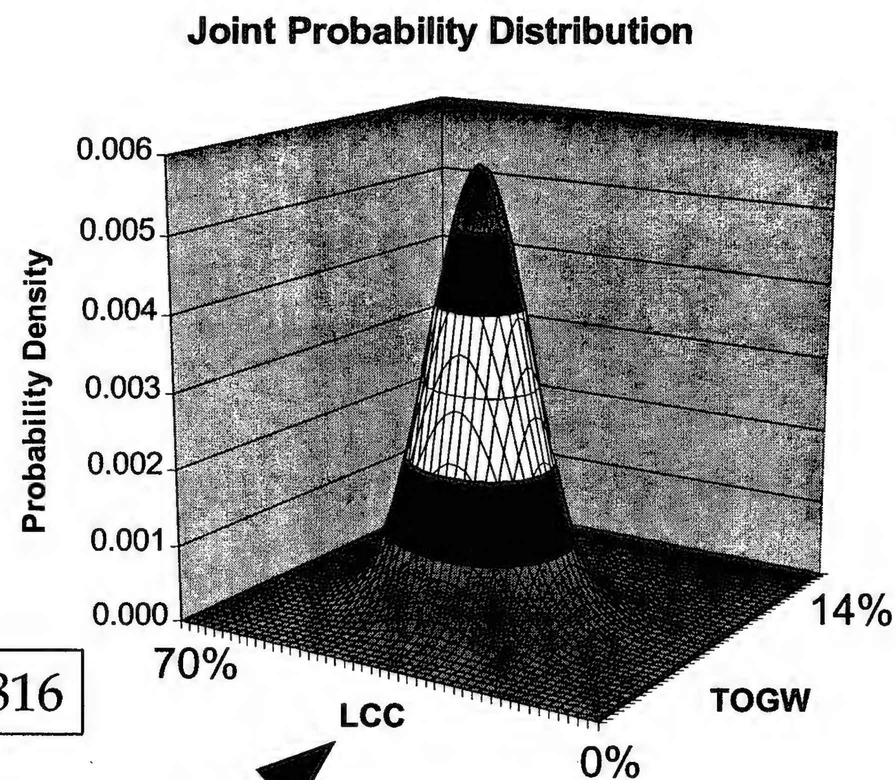



$\mu$=29.23%
$\sigma$=7.69%

$\mu$=6.70%
$\sigma$=1.77%

$\boxed{\rho=-0.1816}$




$$f_{XY}(a,b)=\frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2}}\exp\{\frac{1}{2\rho^2-2}[(\frac{a-\mu_X}{\sigma_X})^2-2\rho(\frac{a-\mu_X}{\sigma_X})(\frac{b-\mu_Y}{\sigma_Y})+(\frac{b-\mu_Y}{\sigma_Y})^2]\}$$

# Results - Method III

## DOE (147 cases)

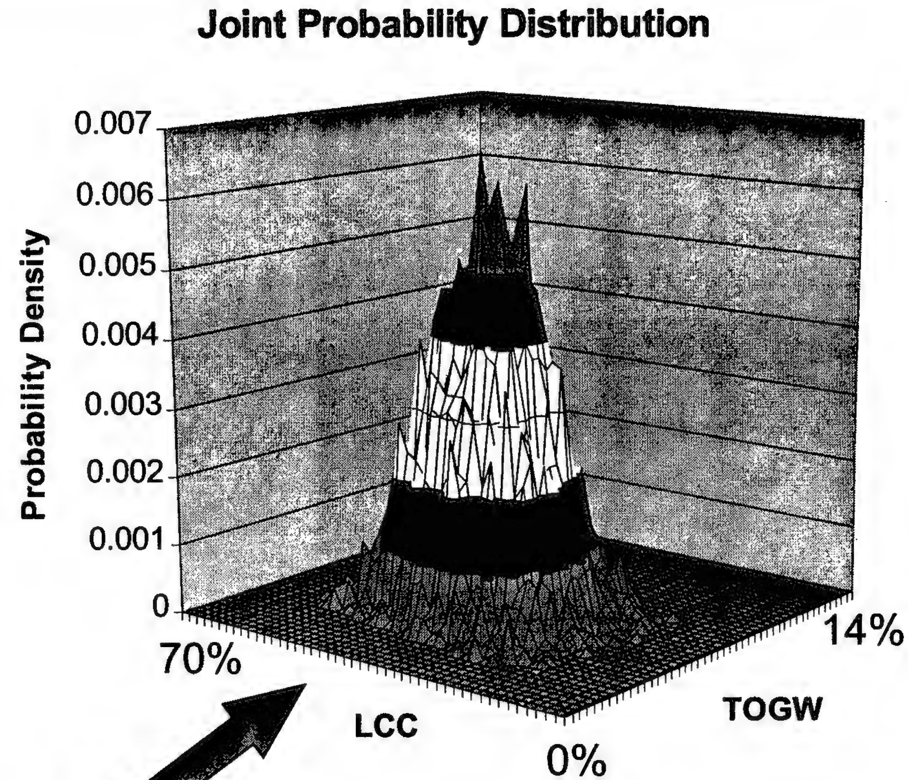
| | LCC | TOGW |
|---|---|---|
| -1 -1 -1 -1 -1 -1 -1 -1 -1 | 10.5% | 5.1% |
| -1 1 -1 1 -1 1 -1 1 -1 | 25.7% | 7.9% |
| 1 -1 -1 1 1 -1 -1 -1 1 | 4.8% | 1.2% |
| • | • | • |

## Response Surface Equation

## Monte Carlo Simulation

10,000 samples from RSE

## Empirical Distribution Function




$$f(LCC,TOGW) = \frac{1}{10,000}\sum_{i=1}^{10,000} I(LCC-\varepsilon < lcc_i \le LCC+\varepsilon, TOGW-\varepsilon < togw_i \le TOGW+\varepsilon)$$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# Results - Method IV

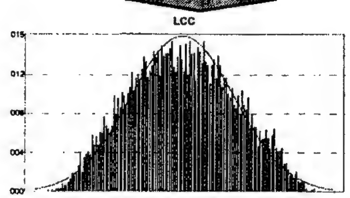
DOE (147 cases)

| | | | | | | | | | LCC | TOGW |
|---|---|---|---|---|---|---|---|---|---|---|
| -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | 10.5% | 5.1% |
| -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 25.7% | 7.9% |
| 1 | -1 | -1 | 1 | 1 | -1 | -1 | -1 | 1 | 4.8% | 1.2% |
| • | | | | | | | | | • | • |

Response Surface Equation

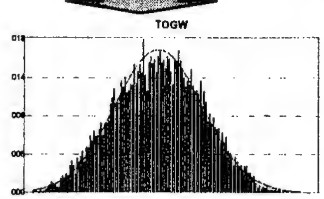
Monte Carlo Simulation

10,000 samples from RSE




$\mu$=28.71%

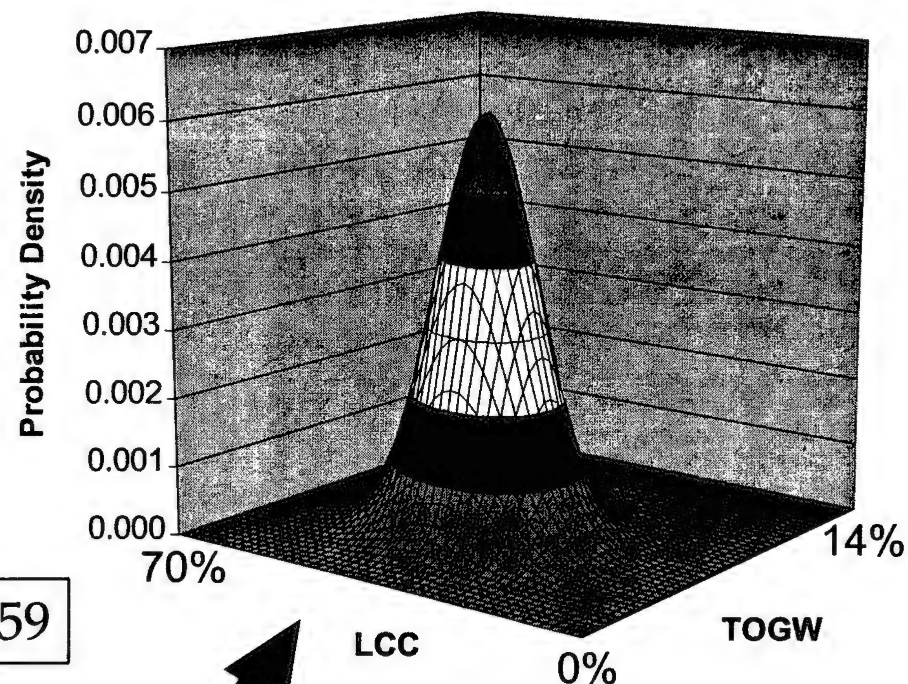
$\sigma$=7.32%




$\mu$=6.66%

$\sigma$=1.76%

$\rho$=-0.159




$$f_{XY}(a,b) = \frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2}}\exp\{\frac{1}{2\rho^2-2}[(\frac{a-\mu_X}{\sigma_X})^2 - 2\rho(\frac{a-\mu_X}{\sigma_X})(\frac{b-\mu_Y}{\sigma_Y}) + (\frac{b-\mu_Y}{\sigma_Y})^2]\}$$

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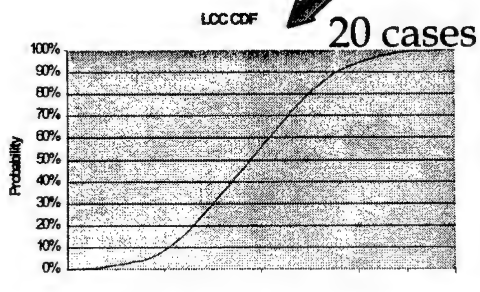
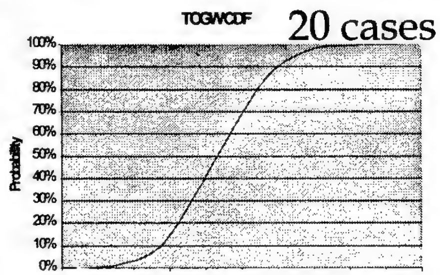
# Results - Method V

AMV



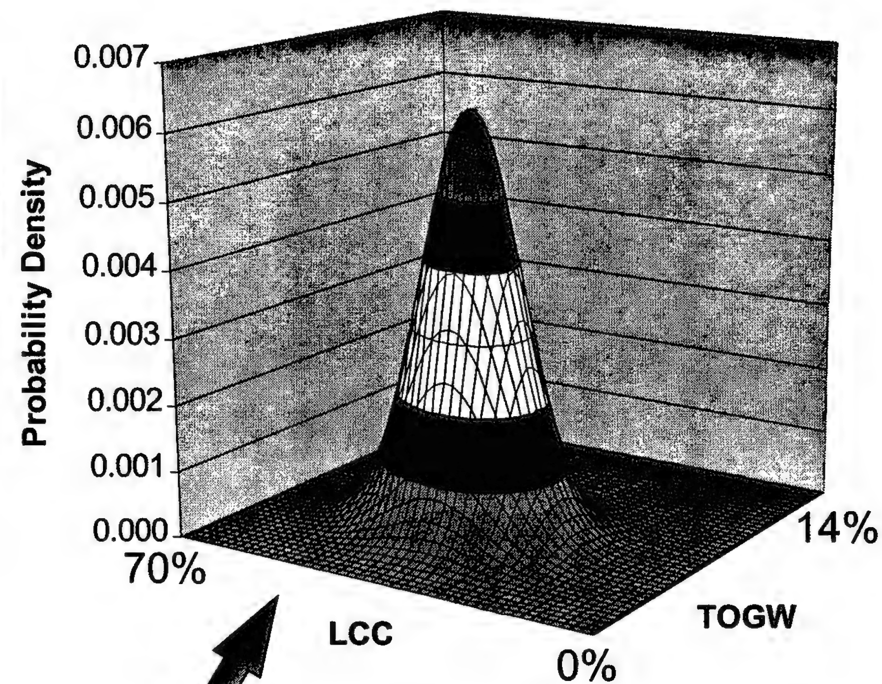

$\mu$=28.46%

$\sigma$=7.27%




$\mu$=6.61% $\sigma$=1.73%

Joint Probability Distribution




$$f_{XY}(a,b)=\frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2}}\exp\{\frac{1}{2\rho^2-2}[(\frac{a-\mu_X}{\sigma_X})^2-2\rho(\frac{a-\mu_X}{\sigma_X})(\frac{b-\mu_Y}{\sigma_Y})+(\frac{b-\mu_Y}{\sigma_Y})^2]\}$$

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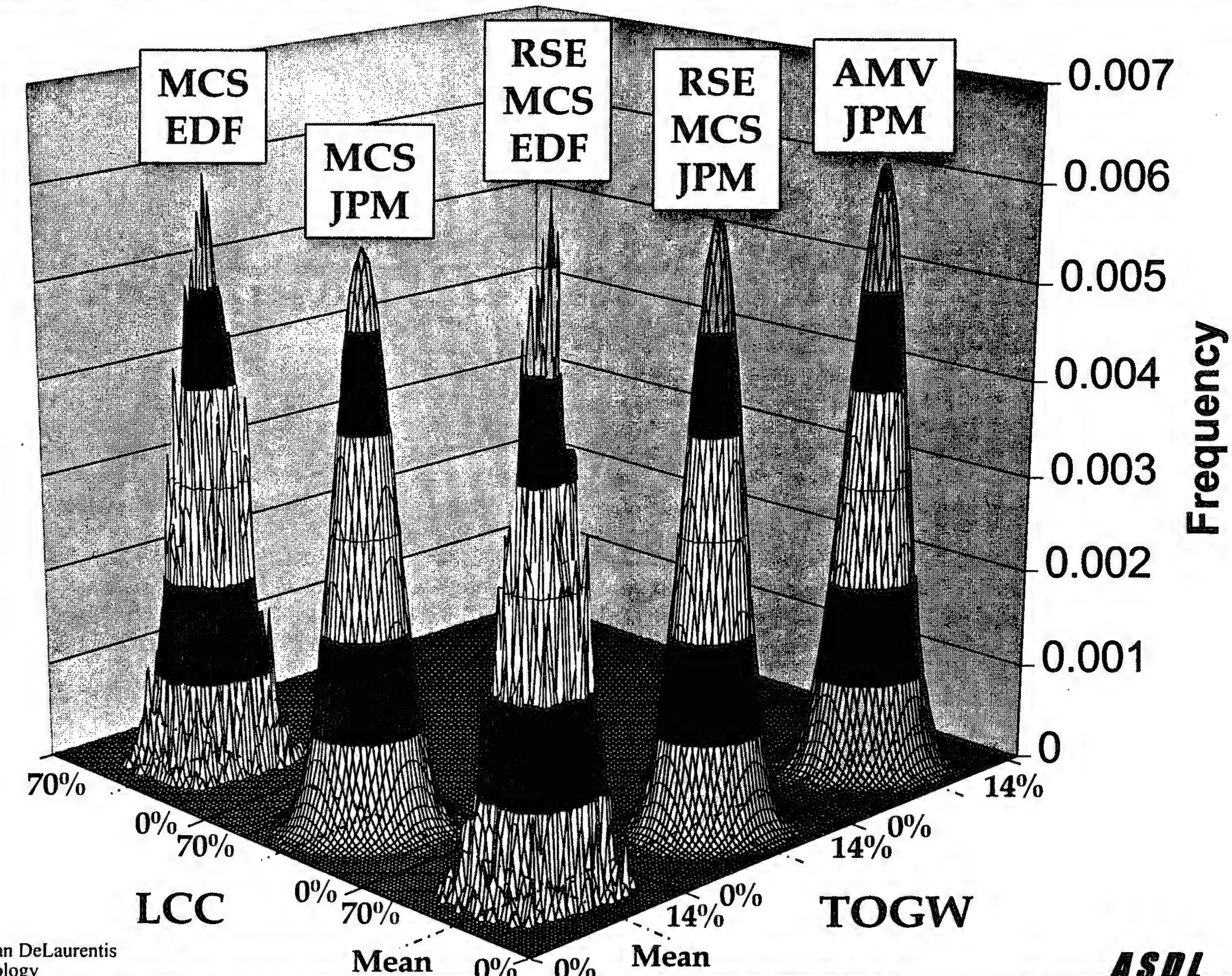
# Comparison of all JPDFs

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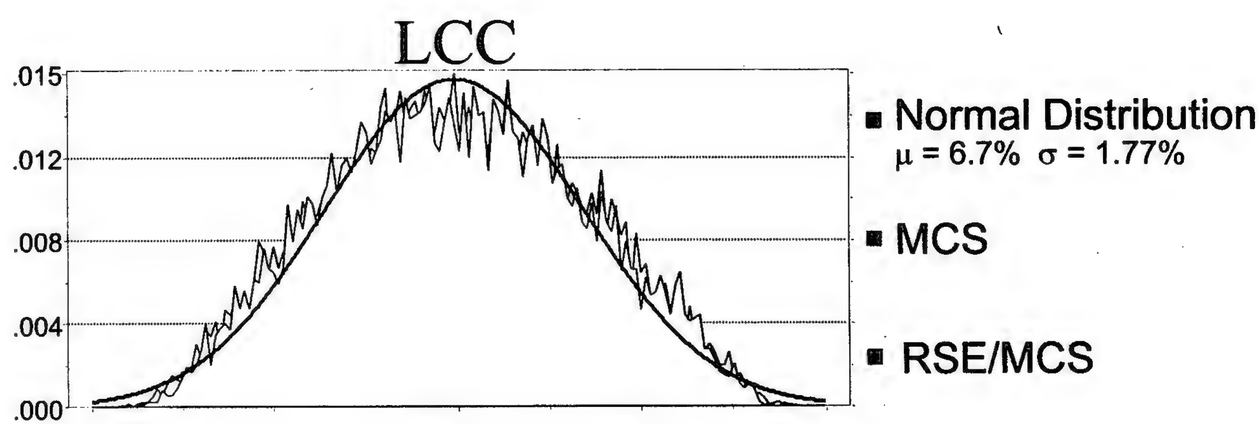
# Comparison of Methods

- Good agreement of Response Surface Equation/Monte Carlo Simulation method and Monte Carlo Simulation directly on analysis code.
- Both distributions are approximated well by the normal distribution (due to nine input variables and the Central Limit Theorem).
- Normal approximation will be even better for non-uniform input distributions.

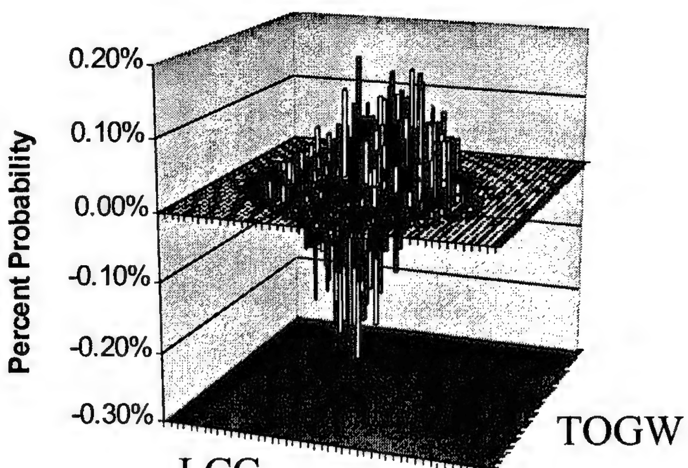


# Comparison of Methods (contd.)

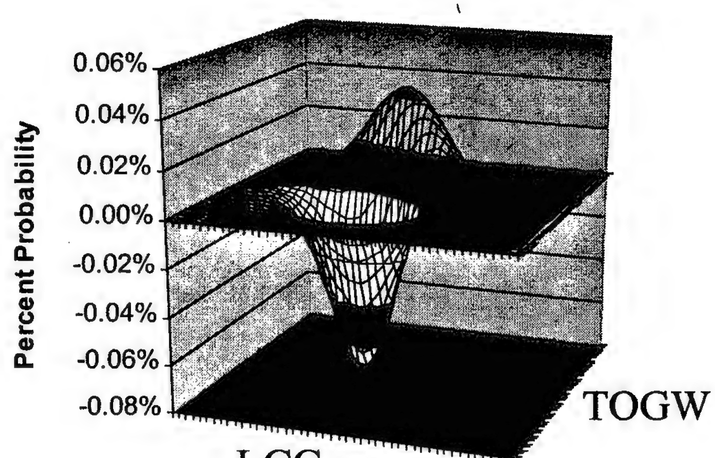
- Comparison of means and standard deviations shows similar prediction capability of methods.

| | MCS/JPM | RSE/JPM | % Difference | AMV/JPM | % Differenc |
|---|---|---|---|---|---|
| $\mu$LCC | 29.23% | 28.71% | -0.40% | 28.46% | -0.60% |
| $\mu$TOGW | 6.70% | 6.66% | -0.04% | 6.61% | -0.09% |
| $\sigma$LCC | 7.69% | 7.32% | -4.73% | 7.27% | -5.43% |
| $\sigma$TOGW | 1.77% | 1.76% | -0.60% | 1.73% | -2.53% |
| Correlation | -0.1816 | -0.1590 | -12.44% | (-0.1816) | - |

MCS/EDF - AMV/JPM




MCS/JPM - AMV/JPM

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# Implementation (cont'd)

**Step 1:** Determine objectives/requirements of customer and designer.

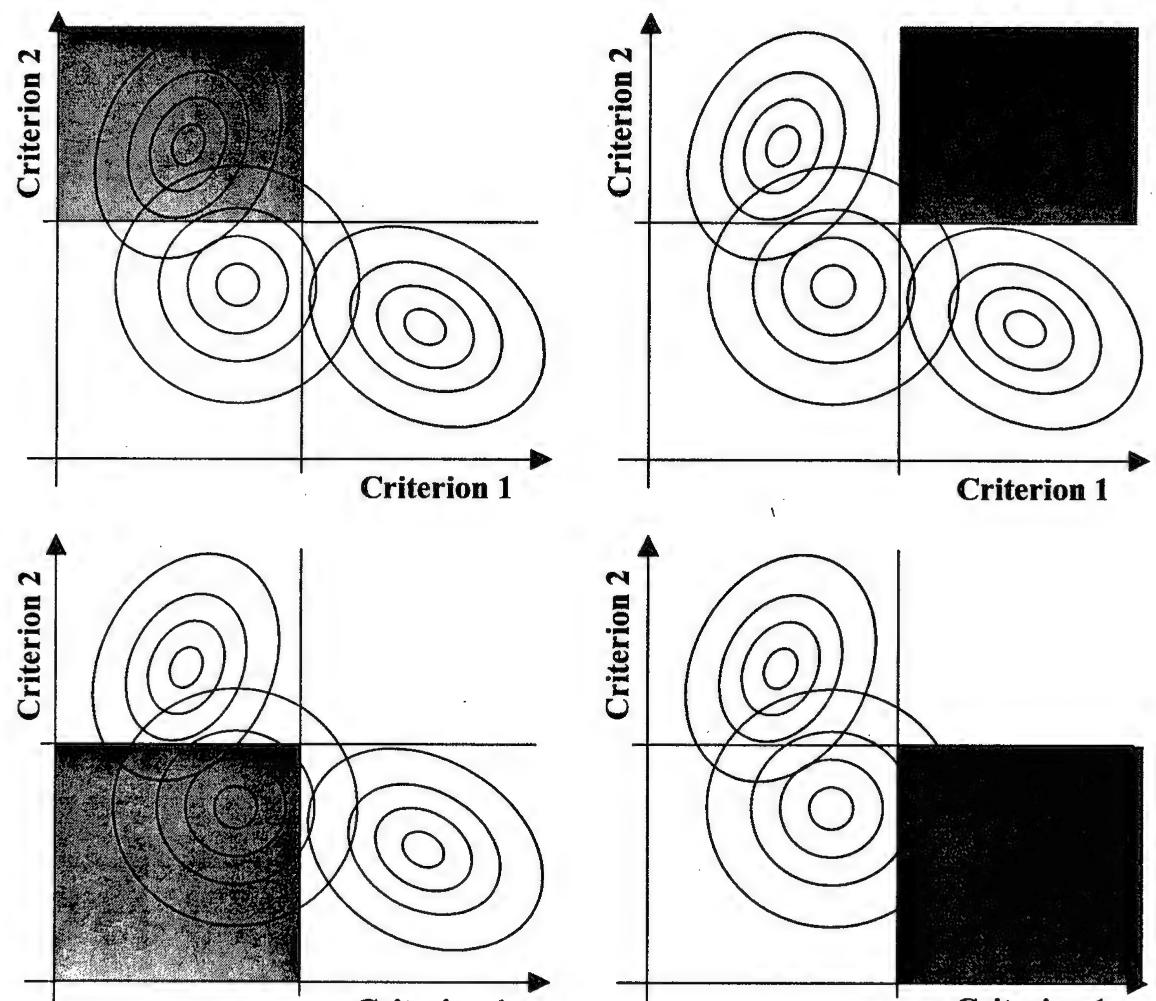
**Step 2:** Assign probability distributions to design assumptions (fix design/control variables).

**Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.

**Step 4:** Determine solution with [illegible] problems: MADM or MODM)

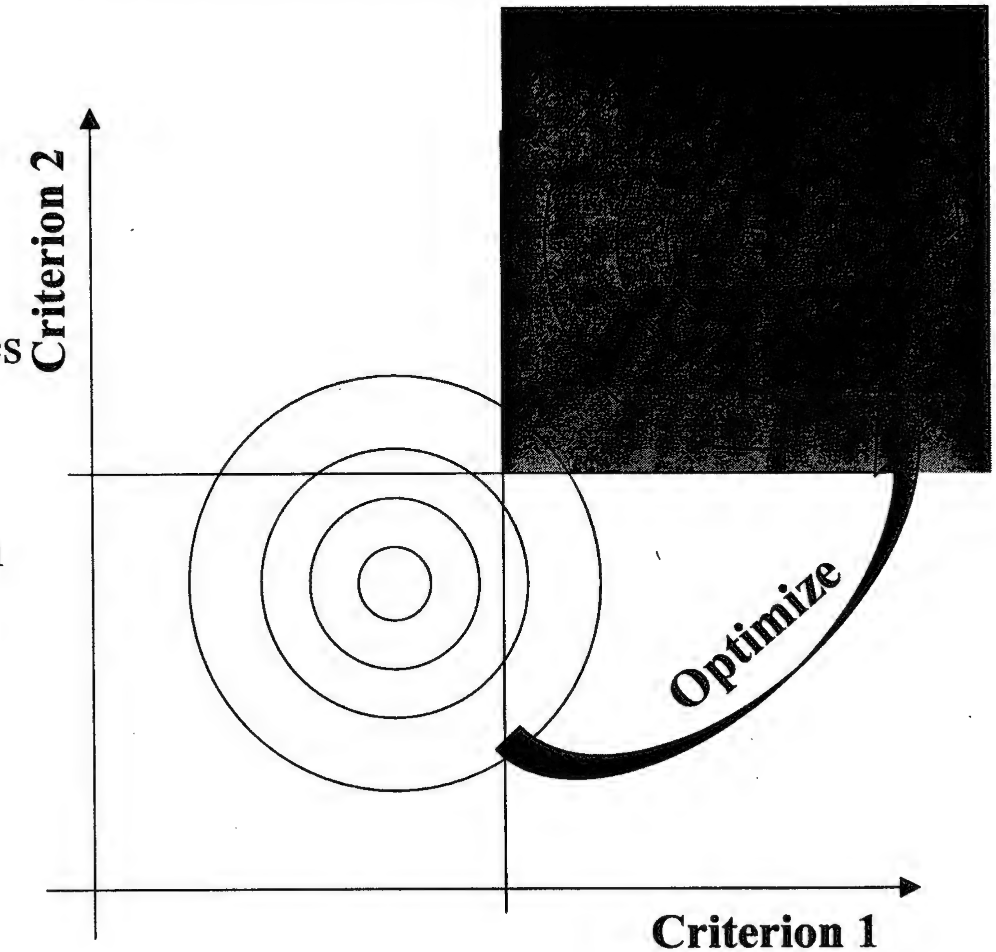
# Step 4 - MADM

- Rank solutions based on joint probability.
- Select solution with highest probability.
- Conduct "What-If" studies for requirements/criteria.



# Step 4 - MODM

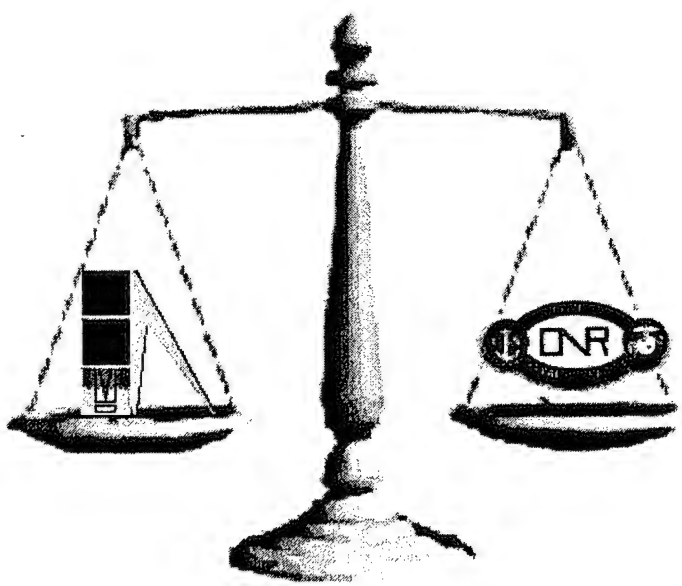
- Use joint probability as an objective function for generic optimizer.
- Use design/control variables as independent variables.
- Determine optimal solution with maximum probability of satisfying all requirements/criteria.



# Conclusions

- A four step joint probabilistic decision making technique was introduced as part of the TIES method.
- Five JPDM methods (MCS/EDF, MCS/JPM, RSE/MCS/EDF, RSE/MCS/JPM, and AMV/JPM) were used to determine the joint probability example study with two criteria.
- JPDM technique is capable of treating uncertain information of early stages in design.
- JPDM technique introduces new objective function to multi criteria decision making: *probability of meeting all operational and design requirements concurrently*.
- JPM needs extension to capture other than normal distributions.

# *A Comprehensive, Robust Design Simulation Approach to the Evaluation/Selection of Affordable Technologies and Systems*




July 21-22, 1999
ONR Affordability Program Grantee Review

Presented By:

**Dr. Dimitri Mavris**
**Dr. Dan DeLaurentis**

Under Grant N00014-97-1-0783

**Aerospace Systems Design Laboratory**
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

# Presentation Outline

1. *Introduction and Research Setting/Summary*

2. *Overall Technical Approach for Affordable Systems Design*

3. *Methods Implementation and Testbed Applications*

4. *Key Advancements in Method Components*

5. *Conclusions/Summary*

# Section 1

1. *Introduction and Research Setting/Summary*

2. *Overall Technical Approach for Affordable Systems Design*

3. *Methods Implementation and Testbed Applications*

4. *Key Advancements in Method Components*

5. *Conclusions/Summary*

# ONR-AMPP Goals and ASDL Objectives

**Overall ONR Goal (AMPP program)**

Develop methods for measuring and predicting affordability during S&T investment decision making for optimal resource allocation

**Results of Georgia Tech ASDL Research Grant**

- A comprehensive, structured, and transparent decision making **methodology** has been developed to guide S&T investment and resource allocation, with the capability for risk reduction, total ownership cost reduction, and performance improvement.

- The baseline tool created to implement this process is called TIES: the *Technology Identification, Evaluation, and Selection* tool TIES is the research testbed as well as research product !

# ASDL-ONR Objective Mapping

**AMPP Objectives:**

- Facilitate S&T Resource Allocation Decisions ✓
- Enable Early Definition/ Assessment of Weapon System Design Trade Spaces ✓
- Assess Impact of Technology Insertion ✓
- Perform Total Cost of Ownership Prediction and reduction for Navy Weapon Systems ✓
- Define Affordability Metrics ✓
- Predict System Affordability ✓

**ASDL Research Thrusts:**

- Multi-Attribute Decision Making
- Technology Impact Forecasting
- Technology Identification, Evaluation, and Selection
- Joint Multivariate Probabilistic Modeling
- Advances in Soft Computing

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# ONR Grant: ASDL Ph.D. Student/Staff Support

Number of Ph.D. Students Supported: 8

| | |
|---|---|
| Ms. Debora Daberkow (ASDL) | Mr. Oliver Bandte (ASDL) |
| Ms. Danielle Soban (ASDL) | Mr. Andy Baker (ASDL) |
| Ms. Elena Garcia (ASDL) | Ms. Linda Wang (ASDL) |
| Ms. Shobana Murali (Math) | Mr. Noppadon Khiripet (EE) |

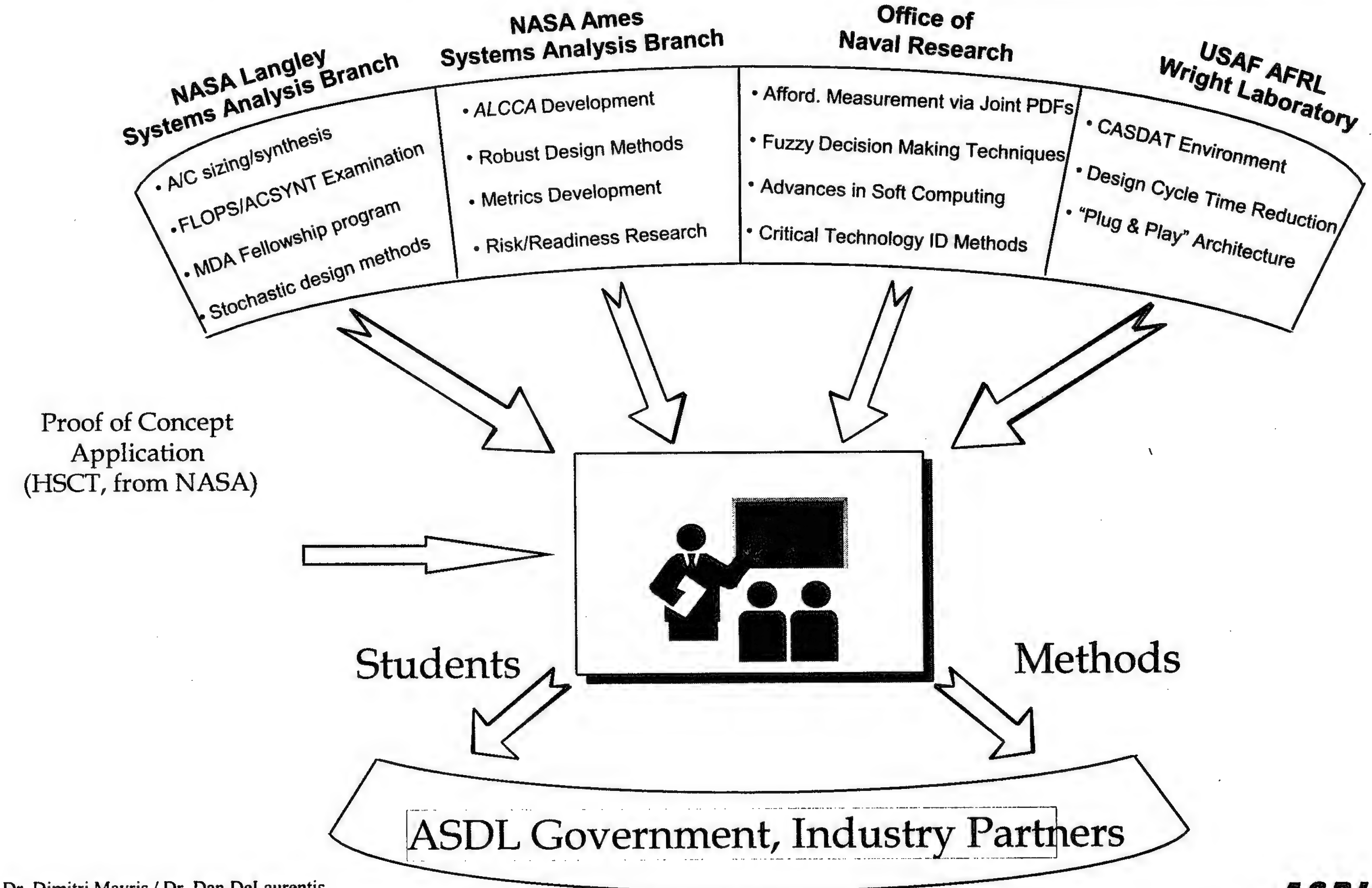
Number of Masters Students Supported: 8

Multidisciplinary Professional Team: 4

| | |
|---|---|
| Dr. Dimitri Mavris (AE) | Dr. Daniel DeLaurentis (AE) |
| Dr. Dan Schrage (AE) | Dr. Mark Hale (AE) |
| Dr. Leonid Bunimovich (Math) | Dr. George Vachtsevanos (EE) |
| Dr. Jimmy Tai(AE) | Dr. Ivan Burdun (AE) |

+ ***Over 40 students exposed to methods in graduate design curriculum***

# Collaborative Research Sponsorship

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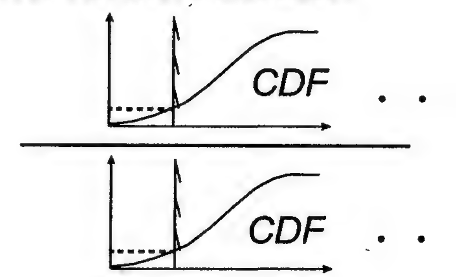
# Definition of Affordability

<u>Affordability</u>: **The ratio of benefits provided or gained from the system over the cost of achieving those benefits**

***In a probabilistic, Modeling & Simulation approach, Risk is inherent in these estimates***

$$S\ \&\ T\ Affordability = \frac{Weapon\ System\ Effectiveness}{Investment\ to\ Achieve\ This\ Effectiveness}$$




## Weapon System Effectiveness- Aircraft Example

**Cost**
- Acquisition cost
- Operation cost
- Maintenance cost
- Aircraft replacement
- Crew replacement training
- RDT&E Cost

**Operational Effectiveness**

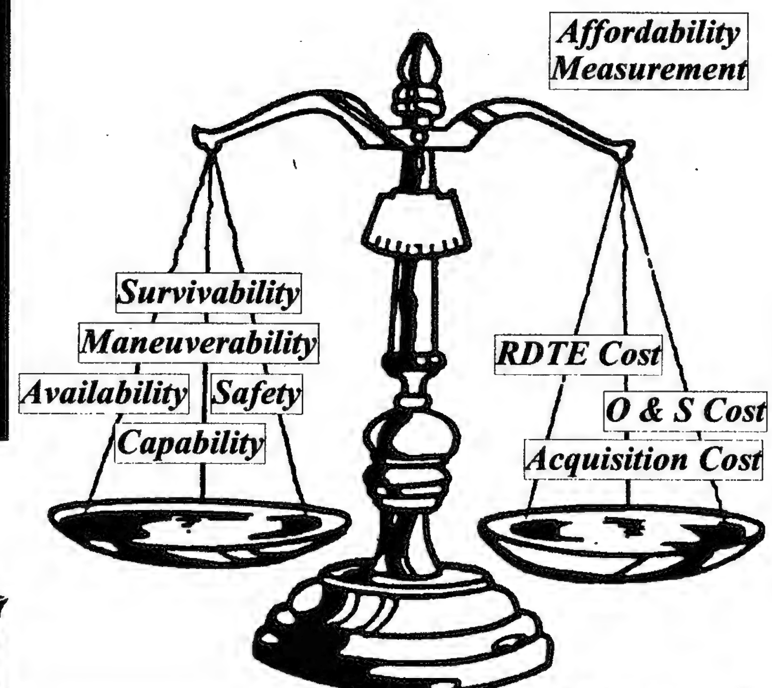
**Survivability**
- Susceptibility
- Vulnerability

**Readiness**
- Maintainability
- Inherent availability
- Reliability
- Logistics support

**Capability**
- Performance
- Maneuverability
- Satisfying mission requirements
- Lethality

**Dependability**
- Safety
- Reliability
- Maintenance defects
- Design defects
- Operations

$$\text{Effectiveness} = k_1(\text{Capability}) + k_2(\text{Survivability}) + k_3(\text{Readiness}) + k_4(\text{Dependability}) + k_5(\text{Life Cycle Cost})$$





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# Science & Technology Return on Investment (ROI)

An Alternate Evaluation Criterion:

$$\frac{\partial\,\text{Benefit}}{\partial\,\text{S\&T Investment}}\;;\;\frac{\partial\,\text{Cost Savings}}{\partial\,\text{S\&T Investment}}\;;\;\frac{\partial\,\text{Risk Reduction}}{\partial\,\text{S\&T Investment}}$$

***ROI*** Assesses the impact that the S&T investment made on the system performance, survivability, safety, ..., developmental, production, support life cycle cost and on averting or reducing risk or by improving the readiness associated with a given technology.

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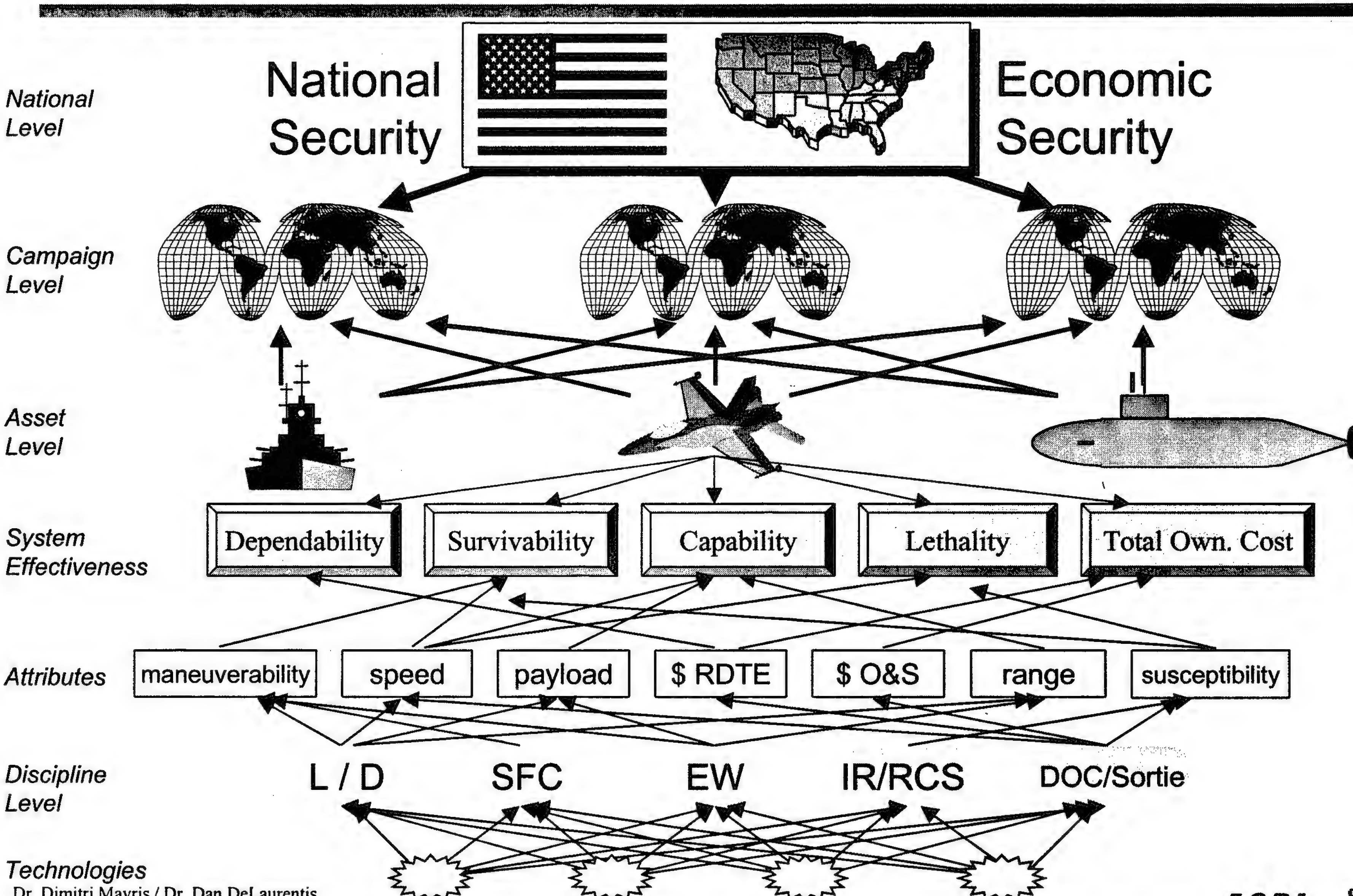
# Problem Definition- Hierarchical Decomposition

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# Technical Areas of Research

ASDL's research for the ONR presented here falls in the following categories:

- Decision-Making methods for Affordability, with and without modeling and simulation capabilities. This area includes:
  - *analysis of alternative concepts and technologies*
  - *joint multivariate probability models for decision making*
  - *multi-attribute methods such as TOPSIS*
  - *decision tree networks with fuzzy inputs.*
- Affordability measurement and prediction (forecasting) of future technology options, in the presence of a variety of uncertainties. This area includes:
  - *Use of Response Surface Models of physics-based analyses*
  - *Uncertainty modeling and use of Fast Probability Integration (FPI)*
  - *Preliminary research into stochastic models and methods*
- Concurrent, physics-based modeling of system requirements and technologies
  - *Nonlinear, constrained equation solver for feasible solutions that trade requirements and technology levels*

***All three of these areas are encompassed in the overall TIES environment***

# Review of Year 1 Results

An innovative, comprehensive method for engineering decision making was created, the Technology Identification, Evaluation, and Selection (TIES) method, populated by:

- *Problem Definition/Brainstorming Tools: QFD, Morphological Matrix, Pugh Matrix*
- *Intelligent Modeling & Simulation and Technology Impact Forecast through Response Surface Methods*
- *Method for rapid assessment of technical feasibility and economic viability*
- *Multi-attribute decision making methods (MADM)*
- *Initiation of a Joint Probability Decision Making (JPDM) model*

Investigation of Advanced Math and Soft Computing Techniques

- *Review and classification of nine emerging techniques*
- *Comparative study of Neural-Network and Response Surface approximations*
- *Employment of Fast Probability Integration (FPI) techniques to assist in probabilistic formulation*
- *Review of advanced tree-network formulations for decision-making under uncertainty and schedule constraints*

# Summary of Year 2 Results

1. Significant enhancements to the TIES affordability environment est. in Year 1
   - *Pilot Studies: Environment prototype for Navy's F-18C, NASA's HSCT, a notional 150 pax transport, and a short-haul civil tiltrotor*
   - *JPDM incorporation and validation; n-variate math model constructed*
   - *Genetic Algorithm for technology combinatorial selection problems*
   - *Fuzzy Decision tree constructed to treat stochastic affordable technology selection problem, an evolution of TIES to include schedule/cost as well as performance*

2. Completion of the investigative research into mathematical and soft computing techniques and stochastics, resulting in:
   - *Web-based database of advanced math and soft computing techniques relevant to affordability measurement and prediction, including current investigators, computer codes, and transition status*
   - *Several implementations of methods (Fuzzy sets, GA's, Neural Networks)*
   - *Roadmap towards stochastic methods established, research goals prioritized*

3. A powerful mathematical tool to examine the simultaneous impact of vehicle requirements & technologies has been created and initially tested on a F/A-18C case, including carrier suitability constraints.

4. Methods have been integrated in Graduate level curriculum

# Research Payoffs: Value Added to USN

- Tradeoff requirements vs. technologies *early in design and procurement* phases, with implications for Navy Total Cost of Ownership (TOC) reduction
  - Ability to identify and assess the impact of new technologies for *Resource allocation planning*
    - Probabilistic *assessment of design, technological, and operational uncertainty*
      - Efficient system *feasibility and economic viability assessment*

- *Reduction in design cycle time and cost*
- *Design for affordability* in an IPPD environment
- Design for "cost as an independent variable" *(CAIV)* as a stochastic process
- Initial implementation of affordability methods to F/A-18C and NASA's HSCT, with further validation on Navy systems proposed

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# Section 2

1. ***Introduction and Research Setting/Summary***

2. ***Overall Technical Approach for Affordable Systems Design - Feasibility/Viability Examination and the TIES Method for Affordable Technology Investment***

3. ***Methods Implementation and Testbed Applications***

4. ***Key Advancements in Method Components***

5. ***Conclusions/Summary***

# Decision Making:

## Two Avenues for Technology Assessment

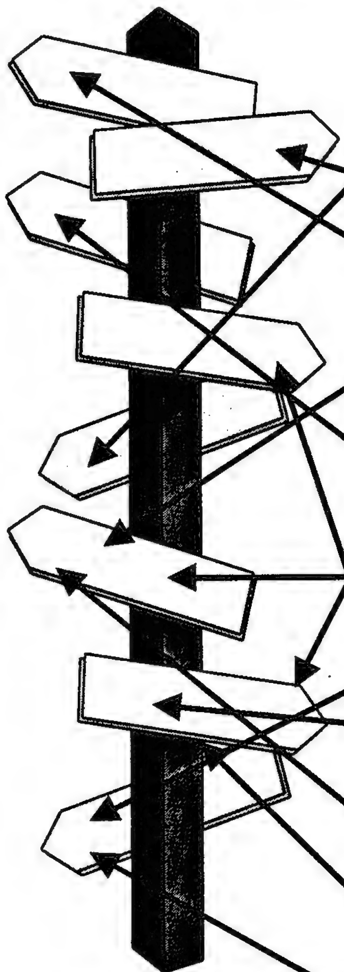
1) Subjective Rankings through QFD, Pugh Diagrams, and Multi-Attribute Decision Making (MADM)

- DoD guiding documents (e.g. DTAPS) & expert opinion are used to establish a mapping of the Navy's warfighting structure
- Through Quality Function Deployment (QFD) and Pugh Diagrams, this mapping is used to subjectively assign importance weights to various technologies accounting for joint warfighting needs
- Multi-Attribute Decision Making (MADM) techniques use results to guide the decision maker to the best solutions

2) Modeling & Simulation (M&S) and Joint Probabilistic Decision Making (JPDM)

- Engineering analyses and physics-based models of technologies are employed in order to obtain objective estimates of technology impacts
- Probabilistic analysis techniques captures uncertainty and risk among multiple, inter-related decision criteria

# Established Techniques + Innovative Methods = *The TIES Affordability Approach*



## Established Techniques

- ★ Response Surface Method (Biology; Ops Research)
- ★ Design of Experiments (Agriculture, Manuf.)
- ★ Quality Function Deployment, Pugh Diagram (Automotive)
- ★ Morphological Matrix (Forecasting)
- ★ MADM techniques (U.S Army, DoD)
- ★ Uncertainty/Risk Analysis (Controls; Finance)
- ★ Simulation-Based Acquisition (DoD Procurement)

## ASDL Innovation

- ★ Feasibility/Viability Identification
- ★ Technology Impact Forecast
- ★ Joint Probabilistic Decision Making
- ★ Stochastic approaches
- ★ Intelligent Integration ⇨ TIES Affordability Meth.

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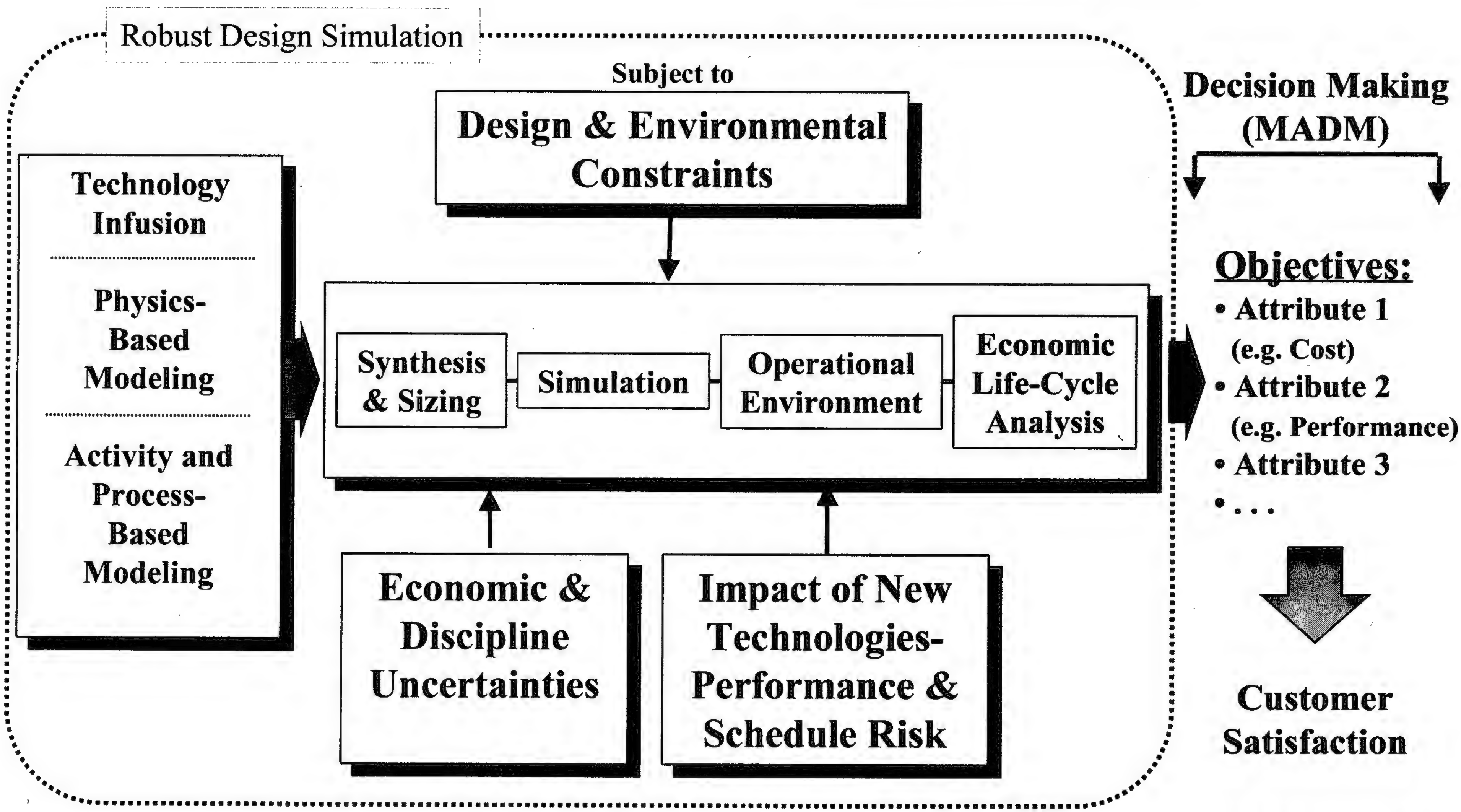
# Physics-Based Modeling and Simulation Environment

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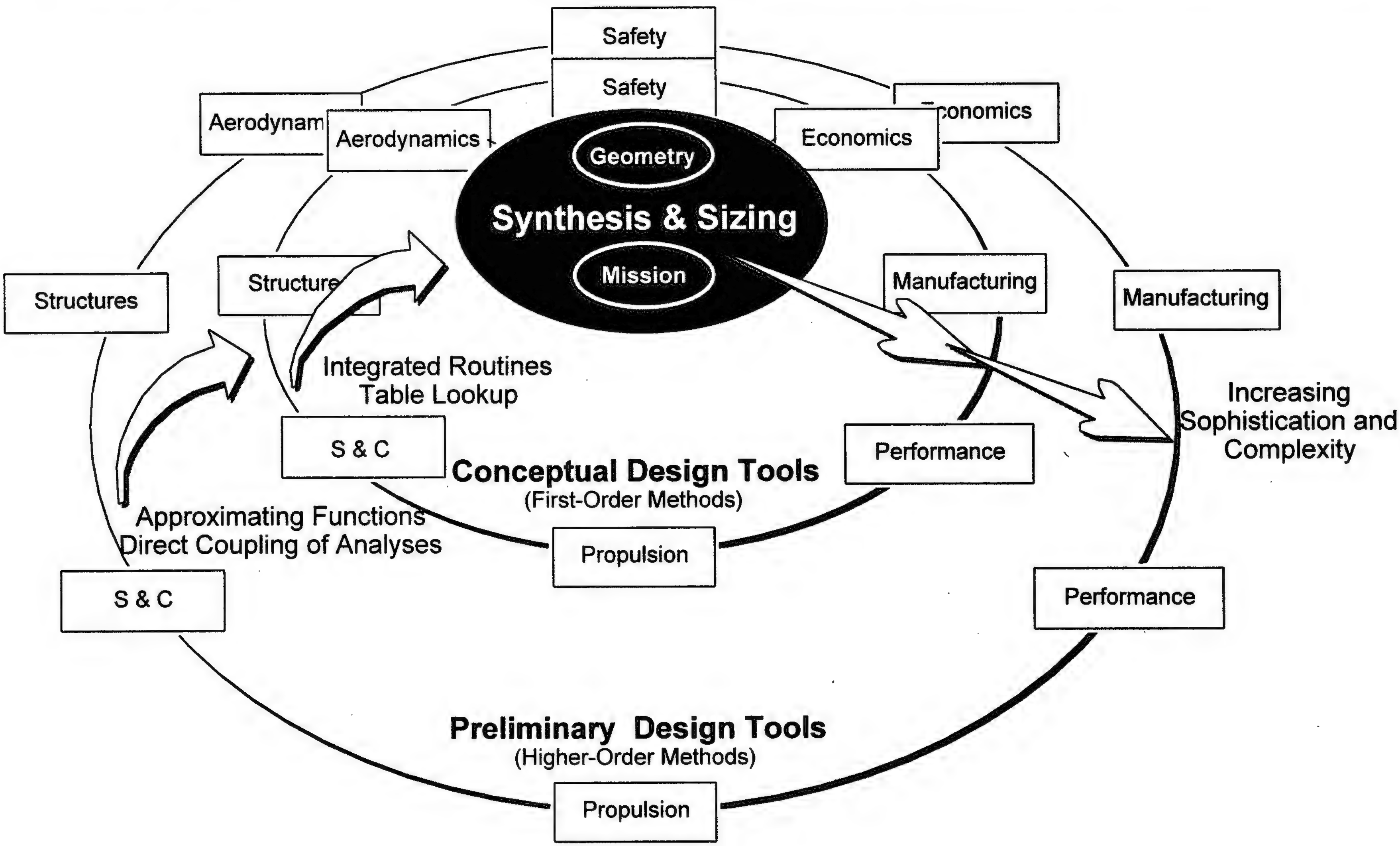
# Creation of a Multi-disciplinary Physics-Based M&S Environment



# Response Surface Methodology (RSM)

- RSM is a multivariate regression technique developed to model the response of a complex system using a simplified equation
- RSM is based on the design of experiments methodology which gives the maximum power for a given amount of experimental effort
- Typically, the response is modeled using a second order quadratic equation of the form:

$$R = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j$$

Where,

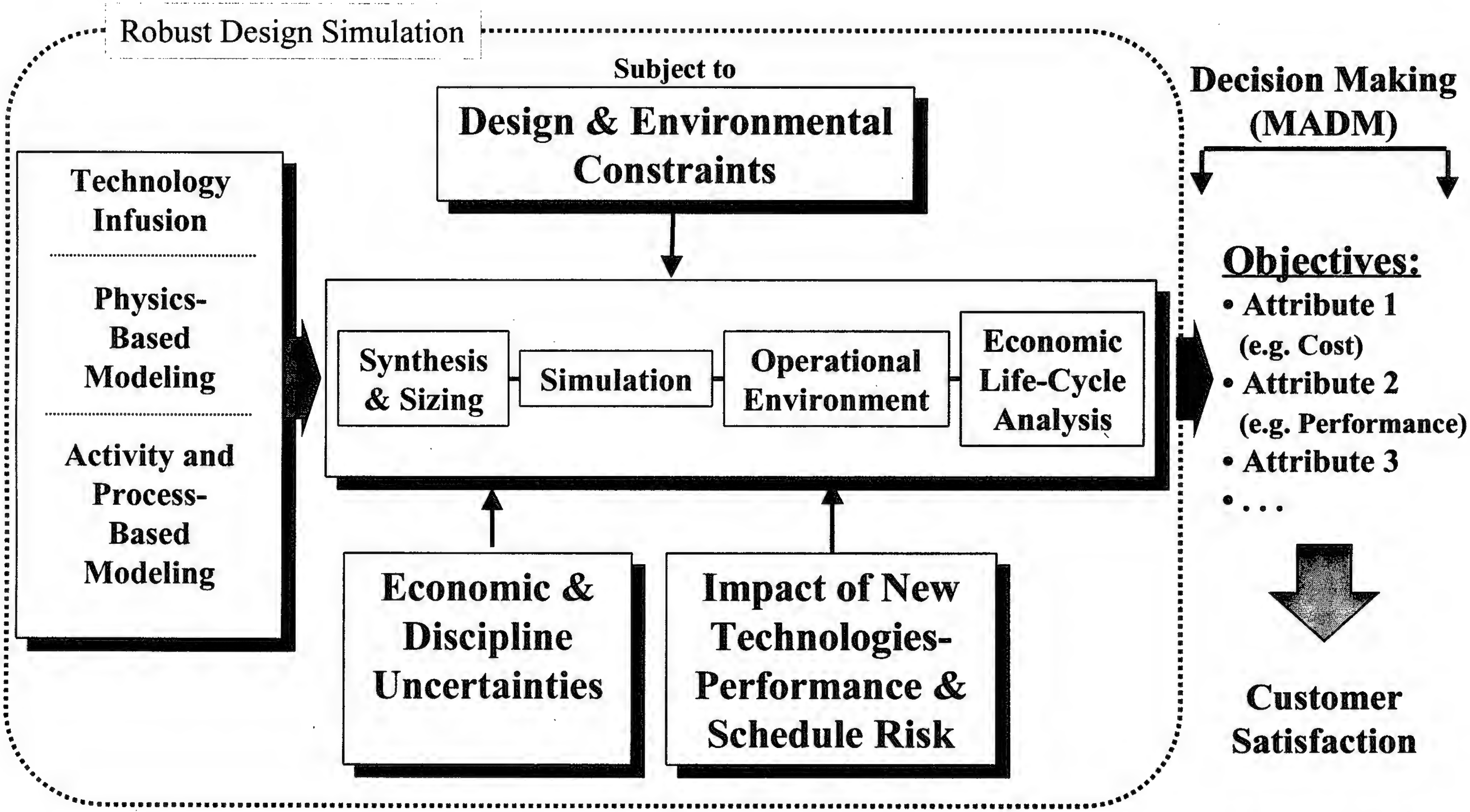
$b_i$ are regression coefficients for the first degree terms
$b_{ii}$ are coefficients for the pure quadratic terms
$b_{ij}$ are the coefficients for the cross-product terms

# Design of Experiments

| Design of Experiments | For 7 Variables | For 12 Variables | Equation |
|---|---|---|---|
| **Full Factorial** | 2,187 | 531,441 | $3^n$ |
| **Central Composite** | 143 | 4,121 | $2^n+2n+1$ |
| **Box-Behnken** | 62 | 2,187 | - |
| **D-Optimal Design** | 36 | 91 | $(n+1)(n+2)/2$ |

| | Factors | | | |
|---|---|---|---|---|
| Run | $X_1$ | $X_2$ | $X_3$ | Response |
| 1 | -1 | -1 | -1 | $y_1$ |
| 2 | +1 | -1 | -1 | $y_2$ |
| 3 | -1 | +1 | -1 | $y_3$ |
| 4 | +1 | +1 | -1 | $y_4$ |
| 5 | -1 | -1 | +1 | $y_5$ |
| 6 | +1 | -1 | +1 | $y_6$ |
| 7 | -1 | +1 | +1 | $y_7$ |
| 8 | +1 | +1 | +1 | $y_8$ |

# Physics-Based Modeling and Simulation Environment

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# Robust Design

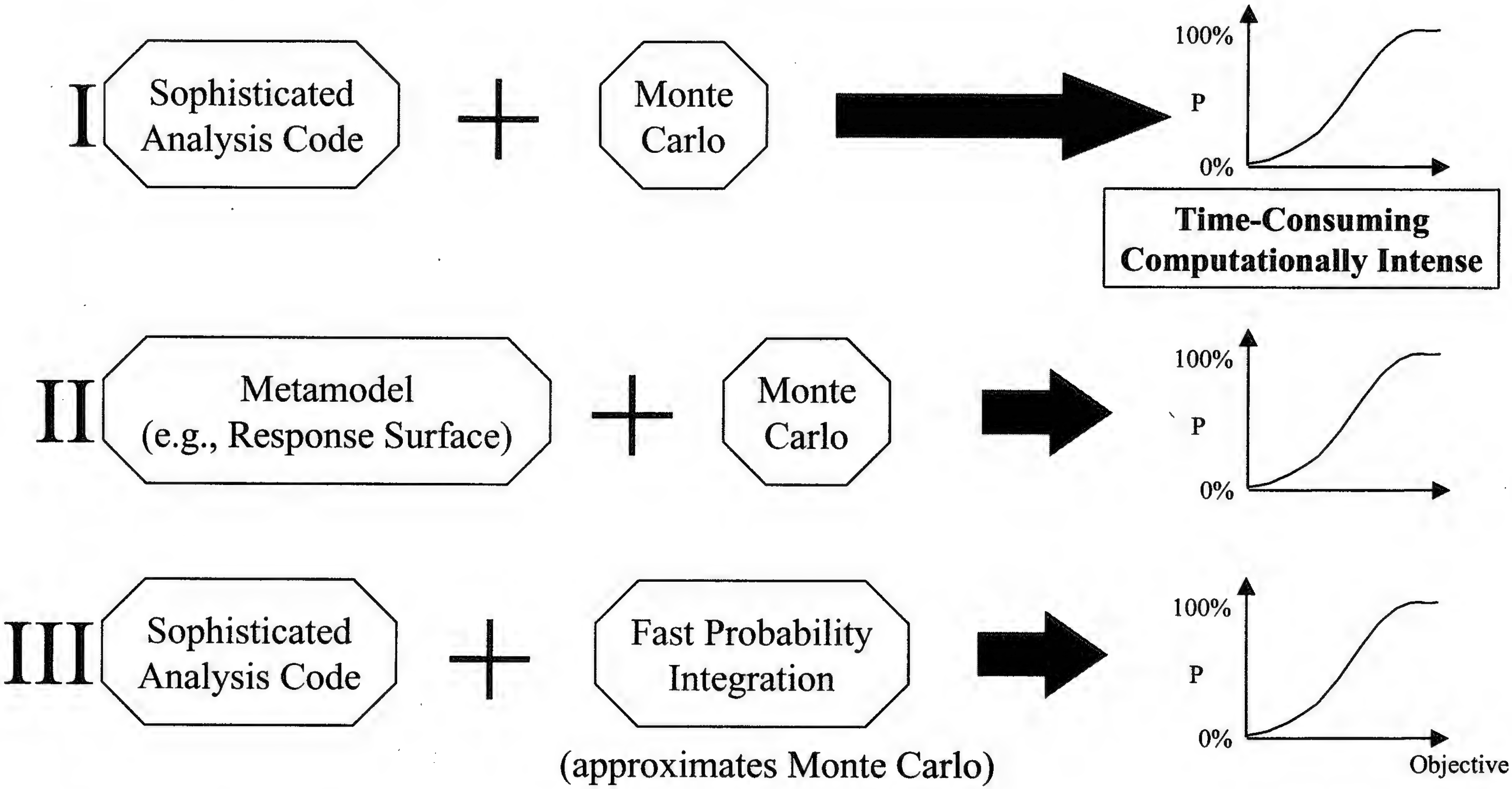
**Robust Design** is the systematic approach to finding *optimum values of design factors* which results in economical designs which *maximize the probability of success*.

A Robust Design is characterized by:

**Technical Feasibility** → satisfies all technical constraints for a given confidence level,

**Viability** → customer's economic targets are also met

# Options for Probabilistic Design

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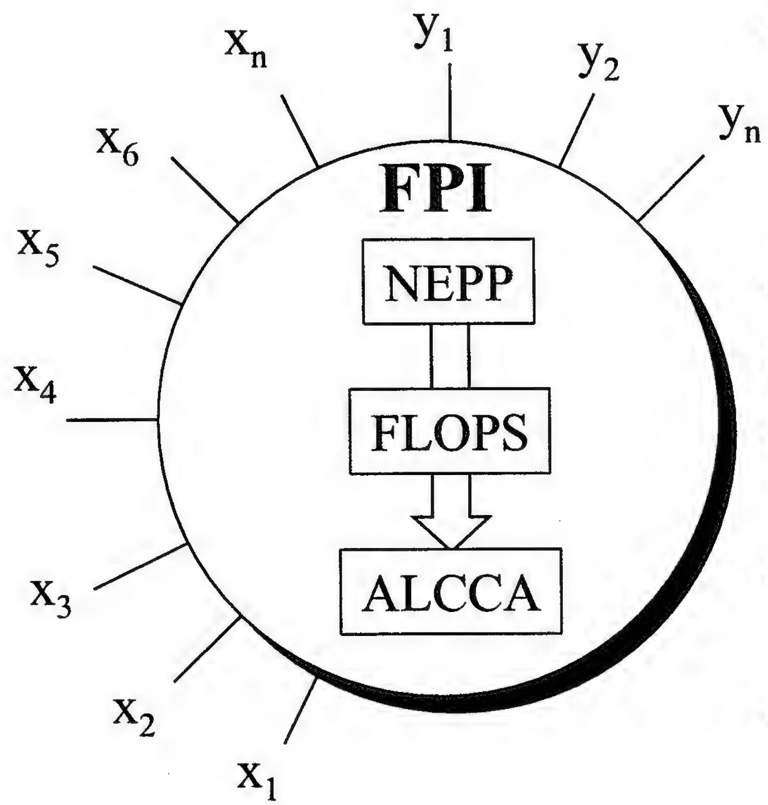
# Fast Probability Integration (FPI)




- FPI manages program execution while handling up to 100 deterministic ($x_i$) or probabilistic ($y_i$) variables, with capability for expansion
- Establishes design feasibility
- Identification of most critical constraints
- Creates probabilistic sensitivity derivatives and CDFs for each objective & constraint
- Assessment of new technologies impact deterministically or probabilistically
- Probabilistic solutions for a set of design variables subject to uncertainty

- Identification of feasible and/or robust solutions, by assigning random distributions to each design variable, within the range of applicability, and allowing for operational and manufacturing uncertainty

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# Characterizing the Feasibility/Viability Method

Q1: What are the measures of success ?

Q2: Is a new technology needed ? i.e. Can optimization satisfy the requirements ?

Q3a: What constraints are being violated ?

Q3b: Can constraints be relaxed ?

Q3c: Can requirements be relaxed? Can they be manipulated/examined simultaneously ?

Q3d: What discipline metric is responsible for this violation ?

Q4a: What is the mapping between technologies and metrics, including adverse effects ?

Q4b: What is the confidence associated with a technology estimate ?

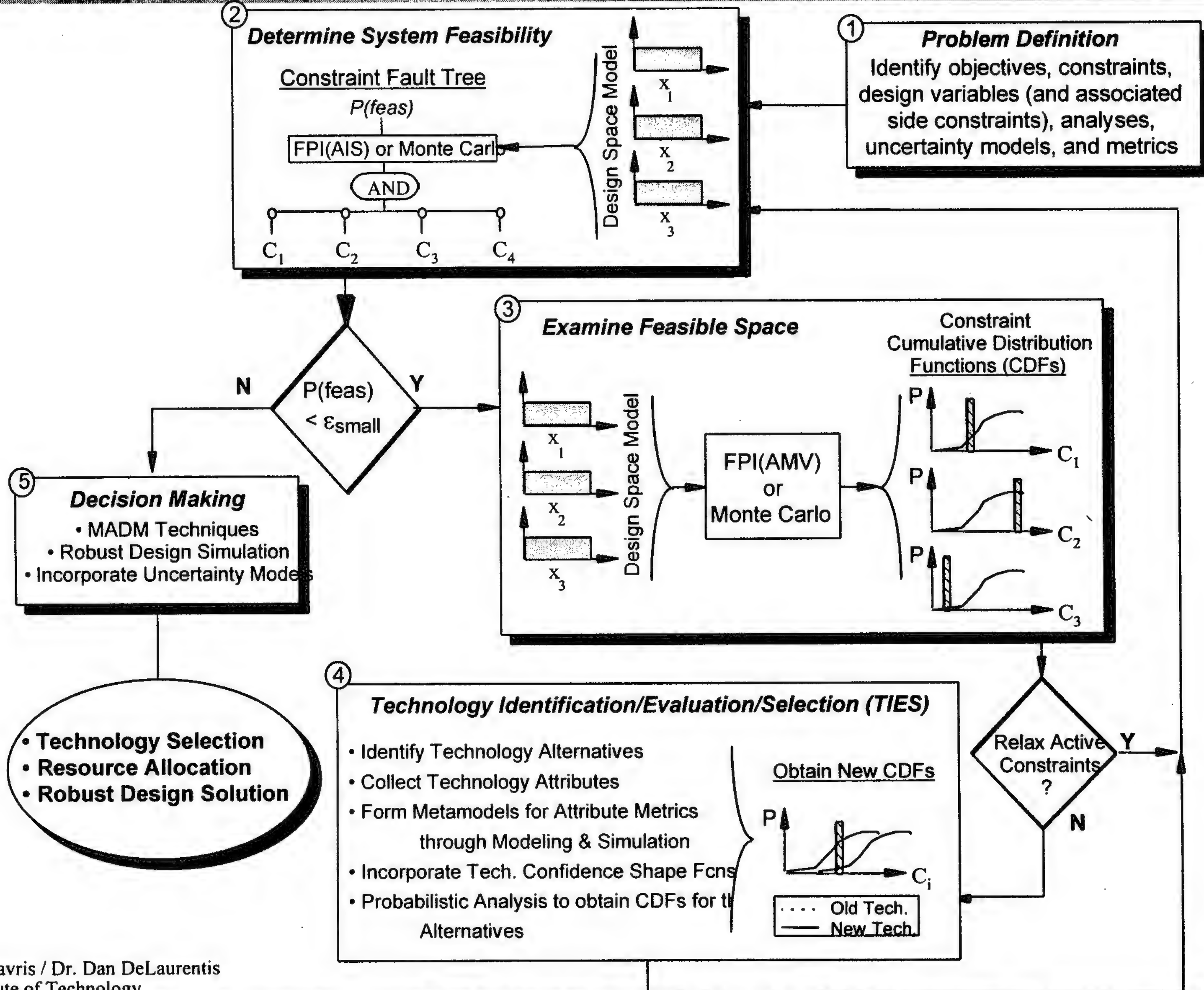
Q4c: What is the optimal resource allocation (including combinations of technologies) ?

Q4d: Multi-Attribute Decision Making methods (MADM) yields best mix of technologies ?

Q5: With technologies and confidence estimates chosen, return to full analysis. Can final design space exploration and robust design optimization improve the result ?

# Roadmap to System Affordability

## Achieving Technical Feasibility & Economic Viability

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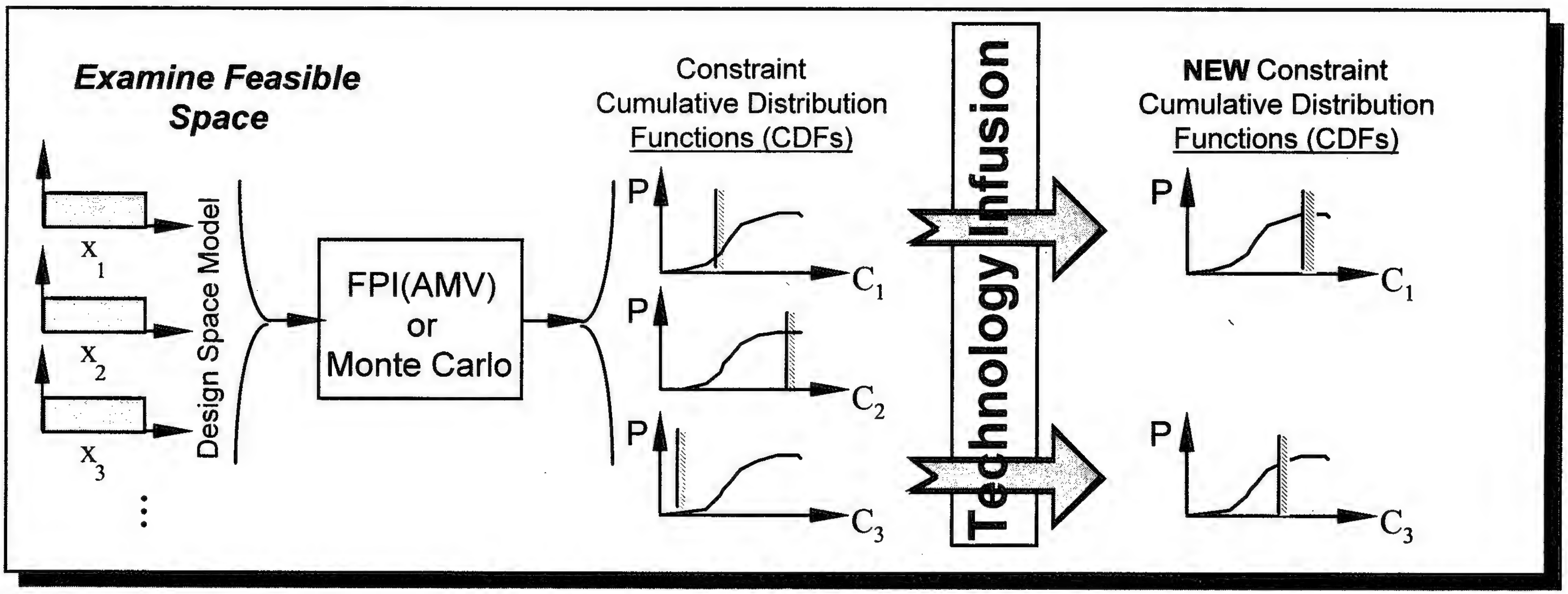
# Feasible Space Examination-
## Technology Infusion





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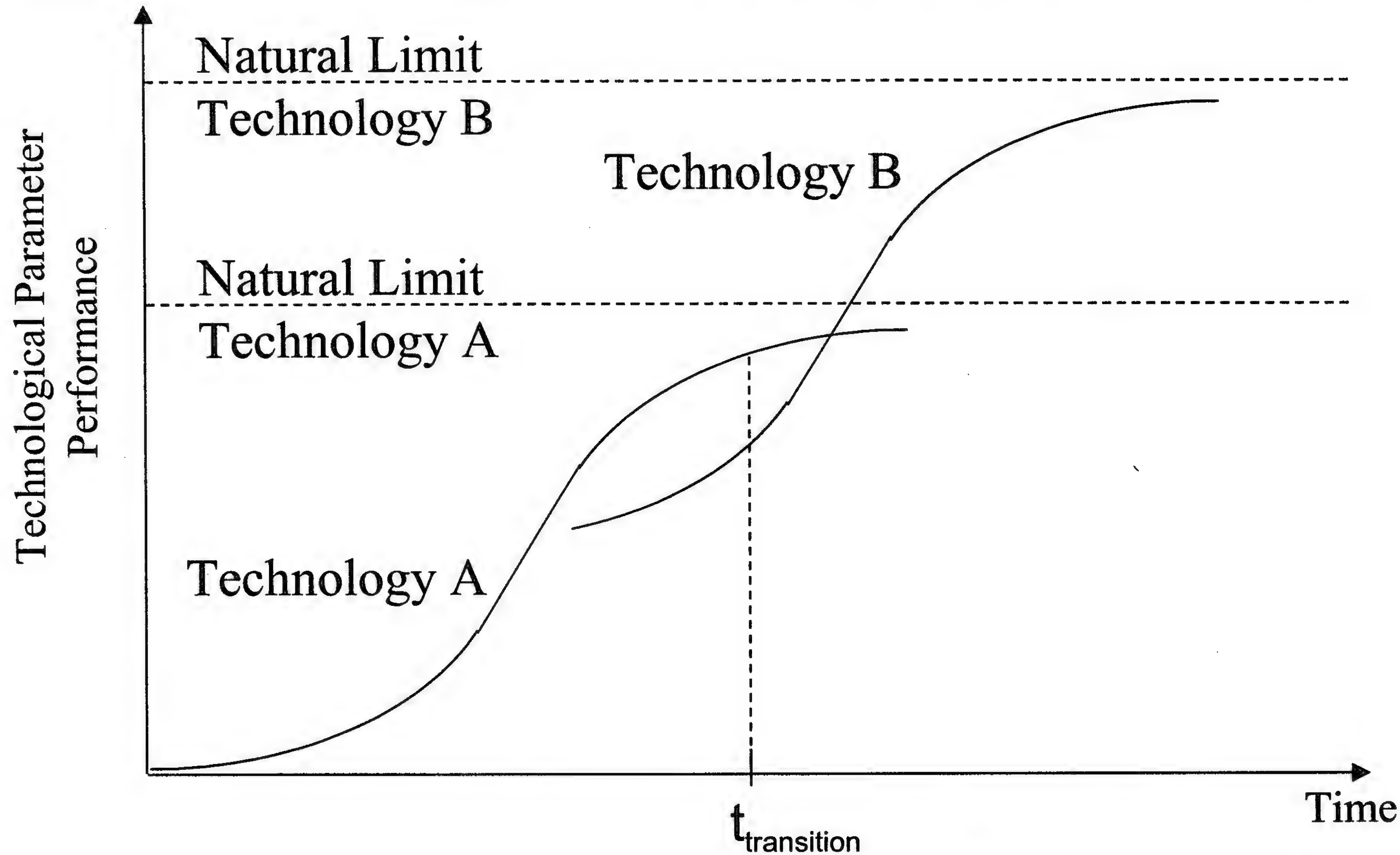
# Technology Substitution




Reference: Twiss, 1992

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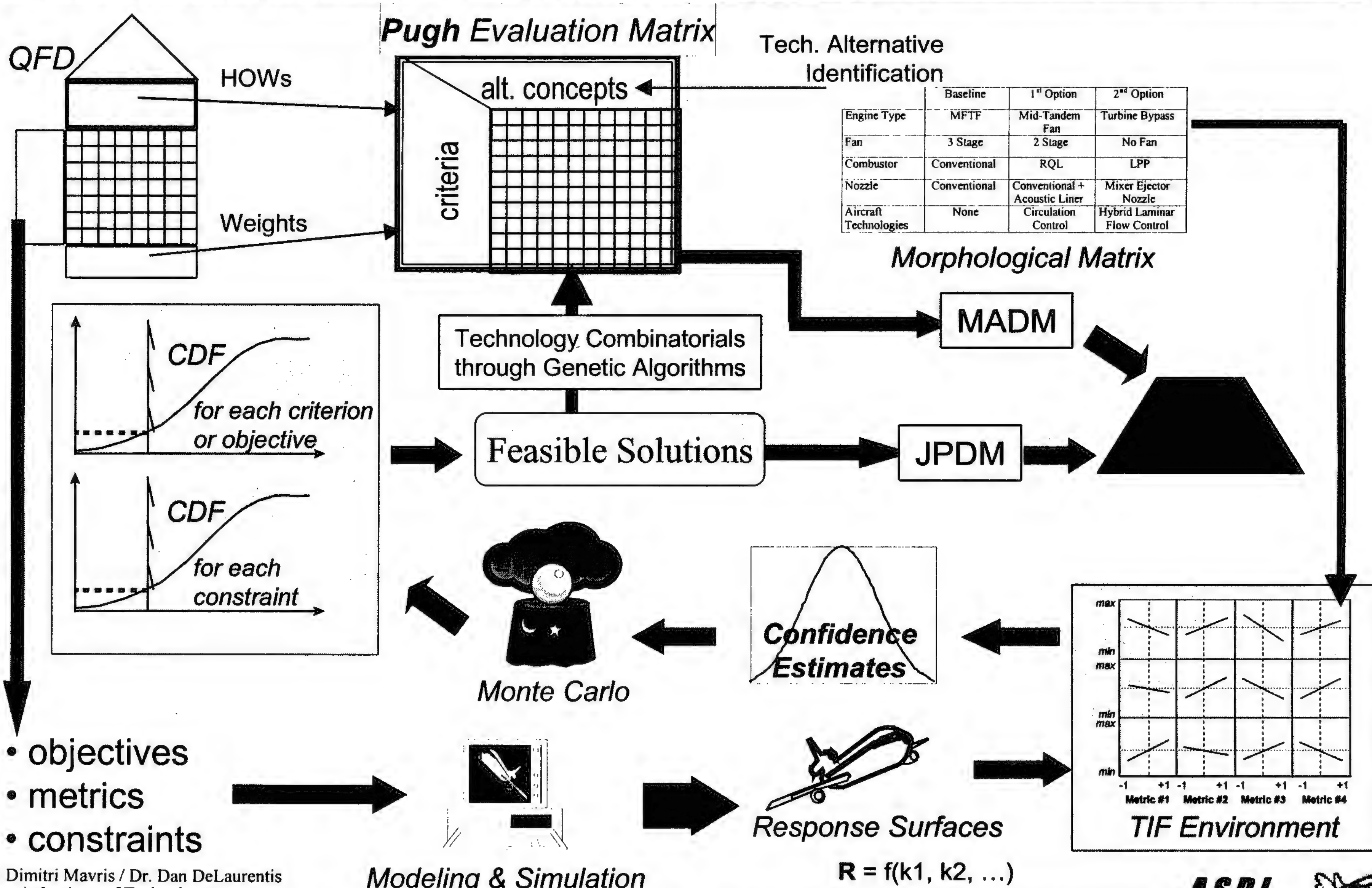
# Technology Identification Evaluation Selection (TIES)




| | Baseline | 1st Option | 2nd Option |
|---|---|---|---|
| Engine Type | MFTF | Mid-Tandem Fan | Turbine Bypass |
| Fan | 3 Stage | 2 Stage | No Fan |
| Combustor | Conventional | RQL | LPP |
| Nozzle | Conventional | Conventional + Acoustic Liner | Mixer Ejector Nozzle |
| Aircraft Technologies | None | Circulation Control | Hybrid Laminar Flow Control |

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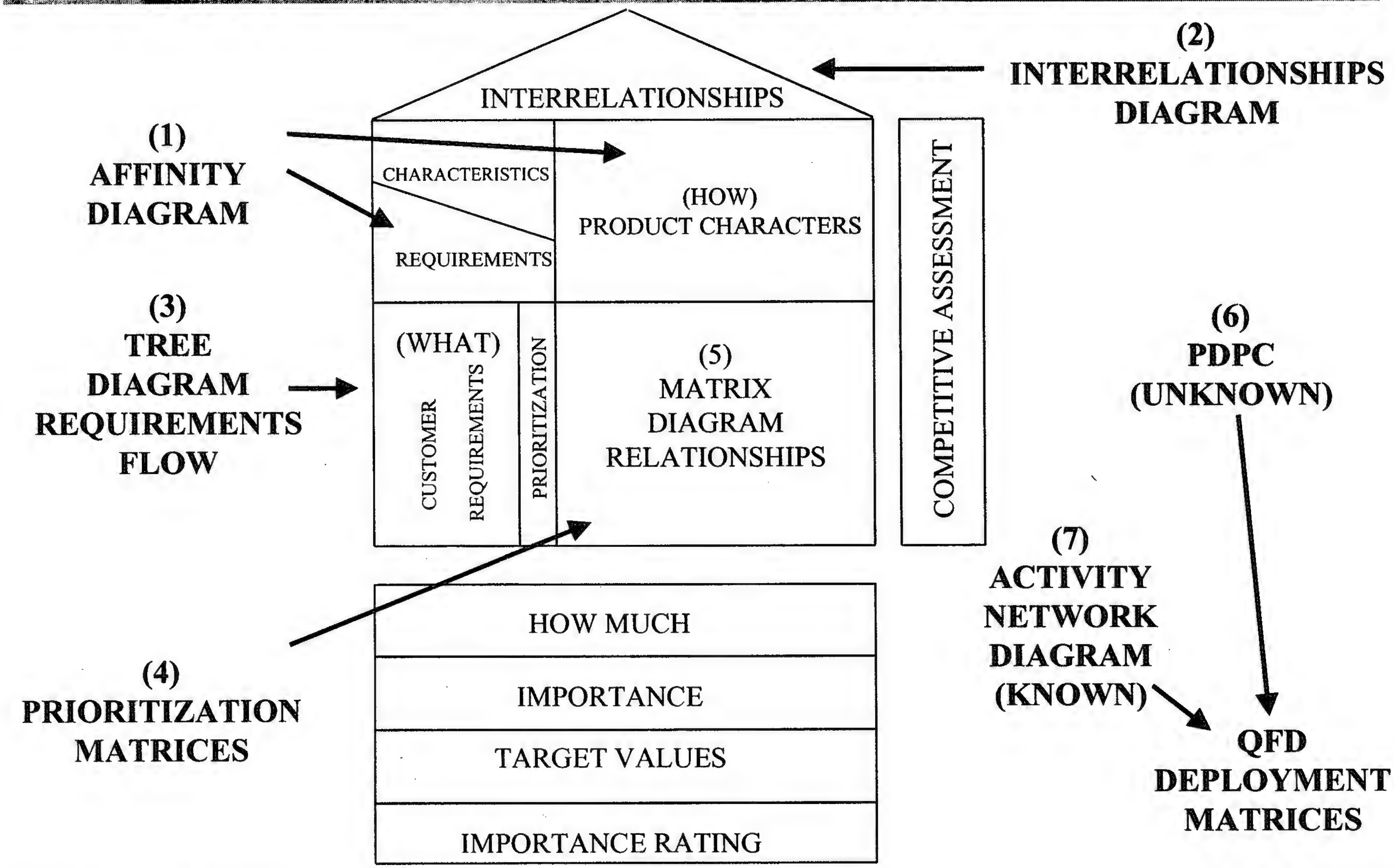
# How the Seven Management and Planning Tools Relate to Quality Function Deployment

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# Morphological Matrix

| | Alternatives / Characteristics | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Config | Vehicle | Wing & Tail | Wing & Canard | Wing, Tail & Canard | Wing |
| | Fuselage | Cylindrical | Area Ruled | Oval | |
| | Pilot Visibility | Synthetic Vision | Conventional | Conventional & Nose Droop | |
| Mission | Range (nmi) | 5000 | 6000 | 6500 | |
| | Passengers | 250 | 300 | 320 | |
| | Mach Number | 2 | 2.2 | 2.4 | 2.7 |
| Propulsion | Type | MFTF | Turbine Bypass | Mid Tandem Fan | Flade |
| | Fan | None | 1 Stage | 2 Stage | 3 Stage |
| | Combustor | Conventional | RQL | LPP | |
| | Nozzle | Conventional | Conventional & Acoustic Liner | Mixed Ejector | Mixer Ejector & Acoustic Liner |
| Aero | Low Speed | Conventional Flaps | Conventional Flaps & Slots | C C | |
| | High Speed | Conventional | LFC | NLFC | HLFC |
| Struct | Materials | Aluminum | Titanium | High Temp. Composite | |
| | Process | Chordwise Stiffened | Spanwise Stiffened | Monocoque | Hybrid |

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# Pugh Evaluation Matrix

## Qualitative Example

| | *Evaluation Criteria* | 1 | 2 | 3 | 4 | ... | n |
|---|---|---|---|---|---|---|---|
| | | *Alternative Concept* | | | | | |
| Airline Economics | $/RPM | + | - | - | + | | |
| | Acquisition Price | + | - | + | S | | Datum Point |
| | Engine Price | - | + | - | - | | |
| | DOC/trip | S | + | + | - | | |
| Manufacturer Economics | Sunk Cost | + | - | - | S | | |
| | Break Even Unit | + | - | - | + | | |
| Environmental | EPNLdB $SL_n$ | + | + | - | - | | |
| | EPNLdB $TO_n$ | - | + | - | - | | |
| | EPNLdB $FO_n$ | + | + | - | - | | |
| Reliability Maintainability | MTBF | + | + | - | + | | |
| | MTTR | + | - | S | + | | |
| | MMH/FH | S | S | + | S | | |
| | Risk | + | S | - | - | | |
| | $\Sigma+$ | 9 | 6 | 3 | 4 | ... | |
| | $\Sigma-$ | 2 | 5 | 9 | 6 | ... | |
| | $\Sigma S$ | 2 | 2 | 1 | 3 | ... | |

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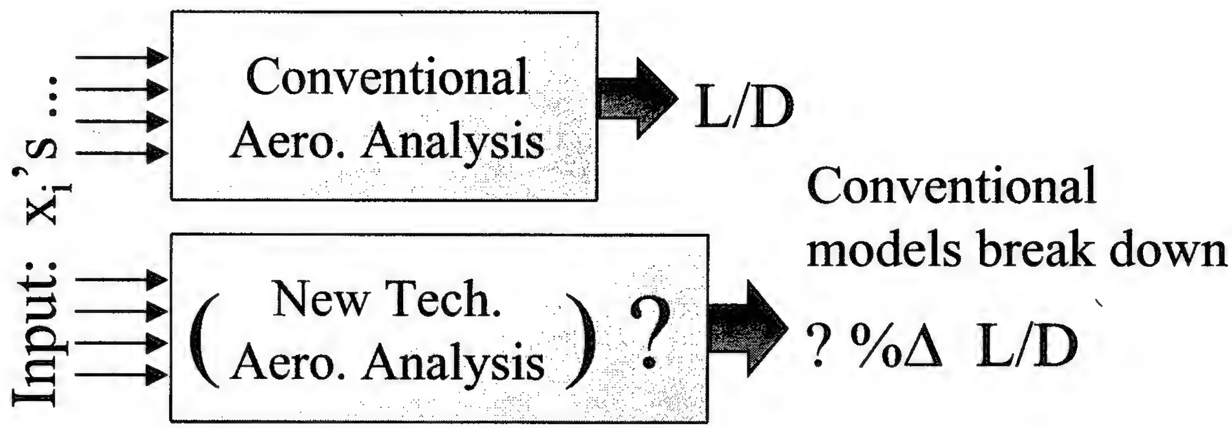
# Mapping Responses to Discipline Metrics via Physics-Based M&S

***Purpose: To Open Feasible Space***

- Formulation in terms of elementary variables does not lend itself to disciplinary or multidisciplinary technology assessment




- The assessment of new technologies must be addressed through the disciplinary metrics (or technology "k" factors) since a mathematical formulation is not yet available

$$\mathit{constraints/objectives} = f(k\_L/D_{sub}, k\_L/D_{sup}, k\_C_{Lmax}, k\_T1, k\_SFC_{sub}, \ldots)$$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# Technology Impact on Metrics

- New technology opens the range of the affected metric through a k-factor:

  $\mathbf{L/D_{new} = k_{L/D}\, L/D_{old}}$ ; where $k_{L/D} = 0.9 \ldots 1.2$ is based on Question 10.
- Select ranges for all metrics affected by new technologies
- The technology is applied to a fixed baseline configuration
- Create a DoE to establish .... for each new technology considered

| $k_{L/Dsub}$ | $k_{L/Dsup}$ | $k_{SFC}$ | $k_n$ | \$/RPM | TOGW | $V_{app}$ | $R_n$ |
|---|---|---|---|---|---|---|---|
| .9 | 1.05 | 0.95 | | 0.125 | 809,781 | 119 | |
| .9 | 1.05 | 0.85 | | 0.129 | 825,432 | 121 | |
| .9 | 0.85 | 0.95 | | 0.137 | 755,593 | 117 | |
| .95 | 0.85 | 0.85 | | 0.133 | 791,024 | 122 | |
| : | : | : | : | : | : | : | : |

- Create RSE based on uncorrelated metrics, since configuration is fixed and metric improvements ($k_m$'s) are selected independently

# Technology Estimates

## Addressing Technology Benefits, Penalties and Confidence

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1. Create functional relationships between Objectives/Constraints and technology metrics | <u>Objective</u> = | $f(L/D_{cruise},$ | $L/D_{TO},$ | $C_{Lmax},$ | $W_{wing},$ | SFC, | MMH/FH, . . .) |
| | <u>Constraint</u> = | $f(L/D_{cruise},$ | $L/D_{TO},$ | $C_{Lmax},$ | $W_{wing},$ | SFC, | MMH/FH, . . .) |
| | | $\downarrow$ | $\downarrow$ | $\downarrow$ | $\downarrow$ | $\downarrow$ | $\downarrow$ |
| 2. Model technology benefits and penalties through metric "k-factors" | (Step Change in Mean) | +10% | +5% | +7% | -3% | +5% | -5% |
| 3. Assign probability distributions to the technology metrics to develop confidence estimates and CDFs | (Variability) | | | | | | |

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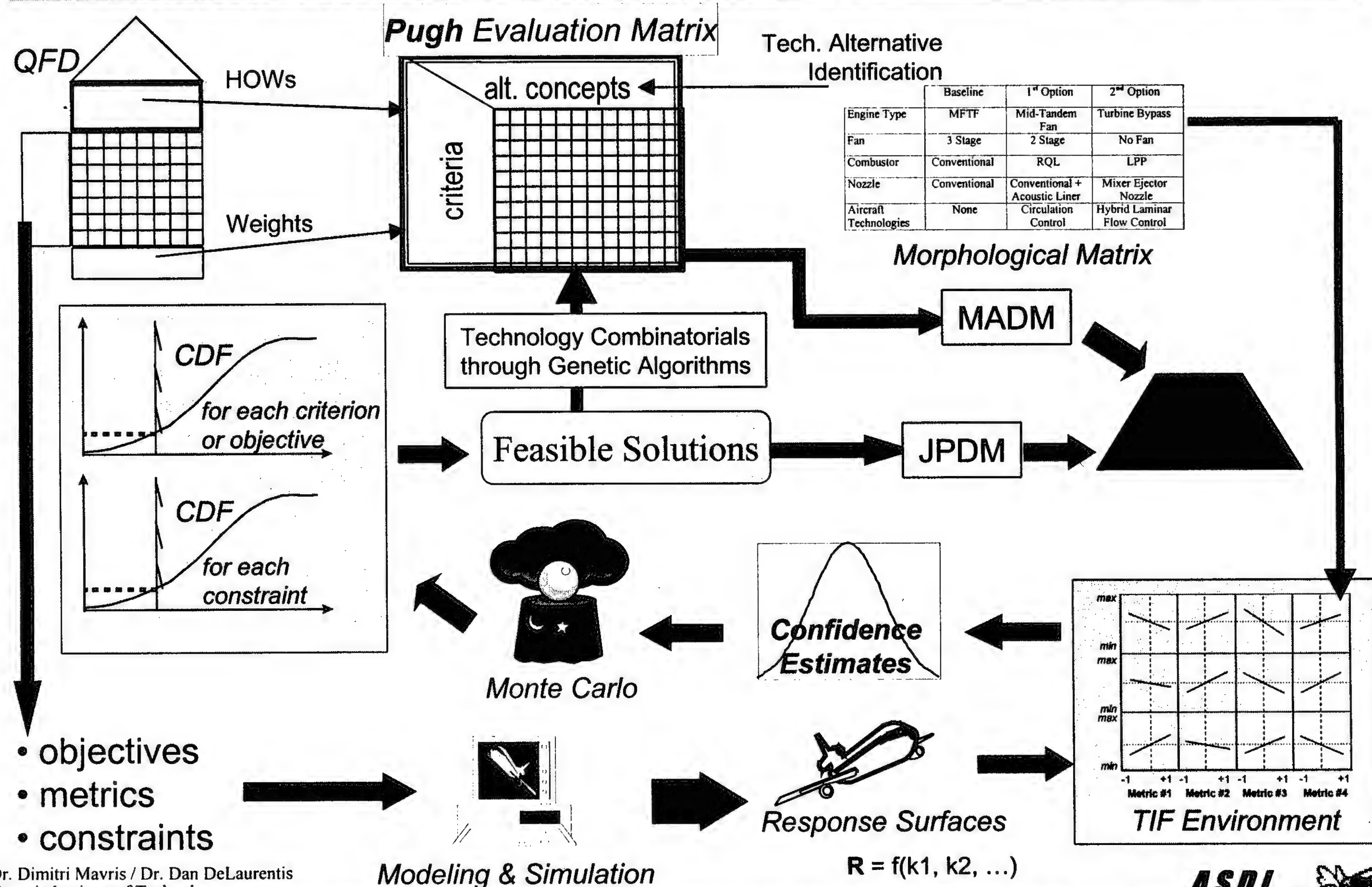
# Technology Identification Evaluation Selection (TIES)




| | Baseline | 1st Option | 2nd Option |
|---|---|---|---|
| Engine Type | MFTF | Mid-Tandem Fan | Turbine Bypass |
| Fan | 3 Stage | 2 Stage | No Fan |
| Combustor | Conventional | RQL | LPP |
| Nozzle | Conventional | Conventional + Acoustic Liner | Mixer Ejector Nozzle |
| Aircraft Technologies | None | Circulation Control | Hybrid Laminar Flow Control |

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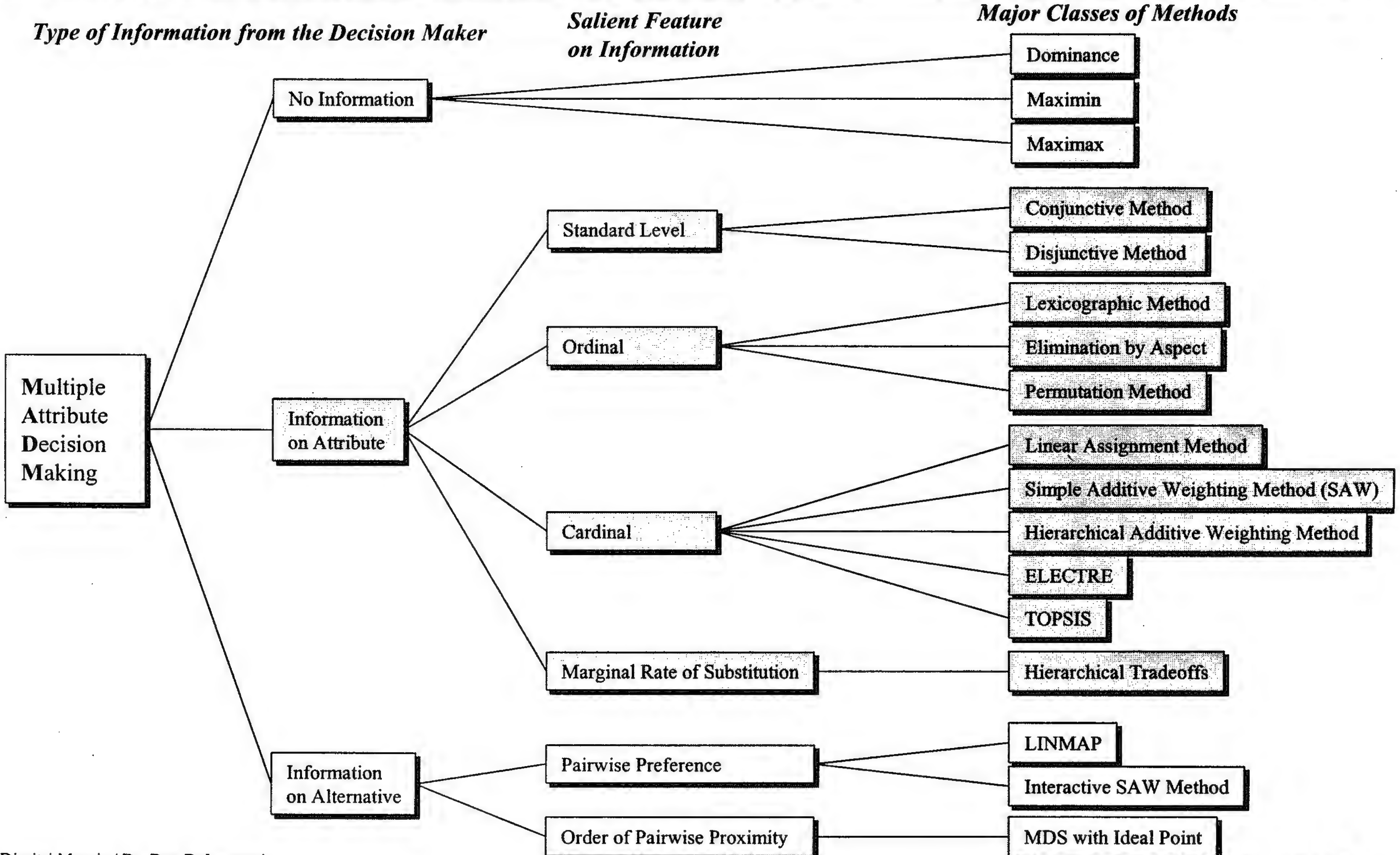
# The MADM Techniques

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# A MADM Choice: TOPSIS

Technique for **O**rder **P**reference by **S**imilarity to **I**deal **S**olution (TOPSIS)

- compensatory and compromising method utilizing preference in the form of weights $w_j$ for each criterion
- best alternative has shortest distance to ideal solution and farthest away from negative-ideal solution

Advantages:

- simplicity
- indisputable ranking obtained

Disadvantages:

- dependent on cardinal information, such as weights
- solution highly dependent on values
- criteria have to have a monotonically increasing or decreasing utility to the decision-maker

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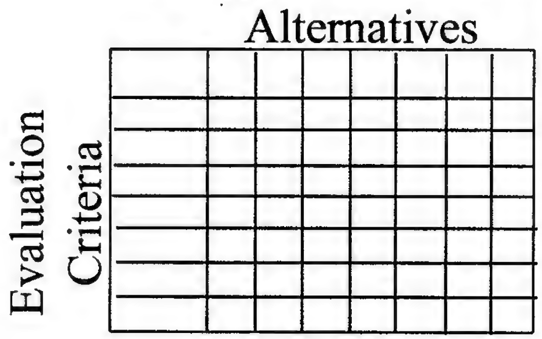
# Multi-Attribute Decision Making (MADM)

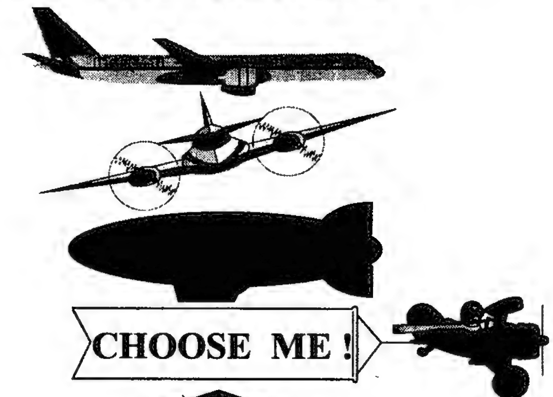
## Pugh Matrix



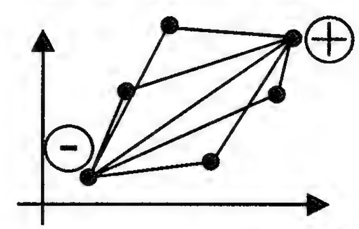

## +/- Ideal Solution

Based on best criteria values

## Ranked Alternatives




## Euclidean Differences

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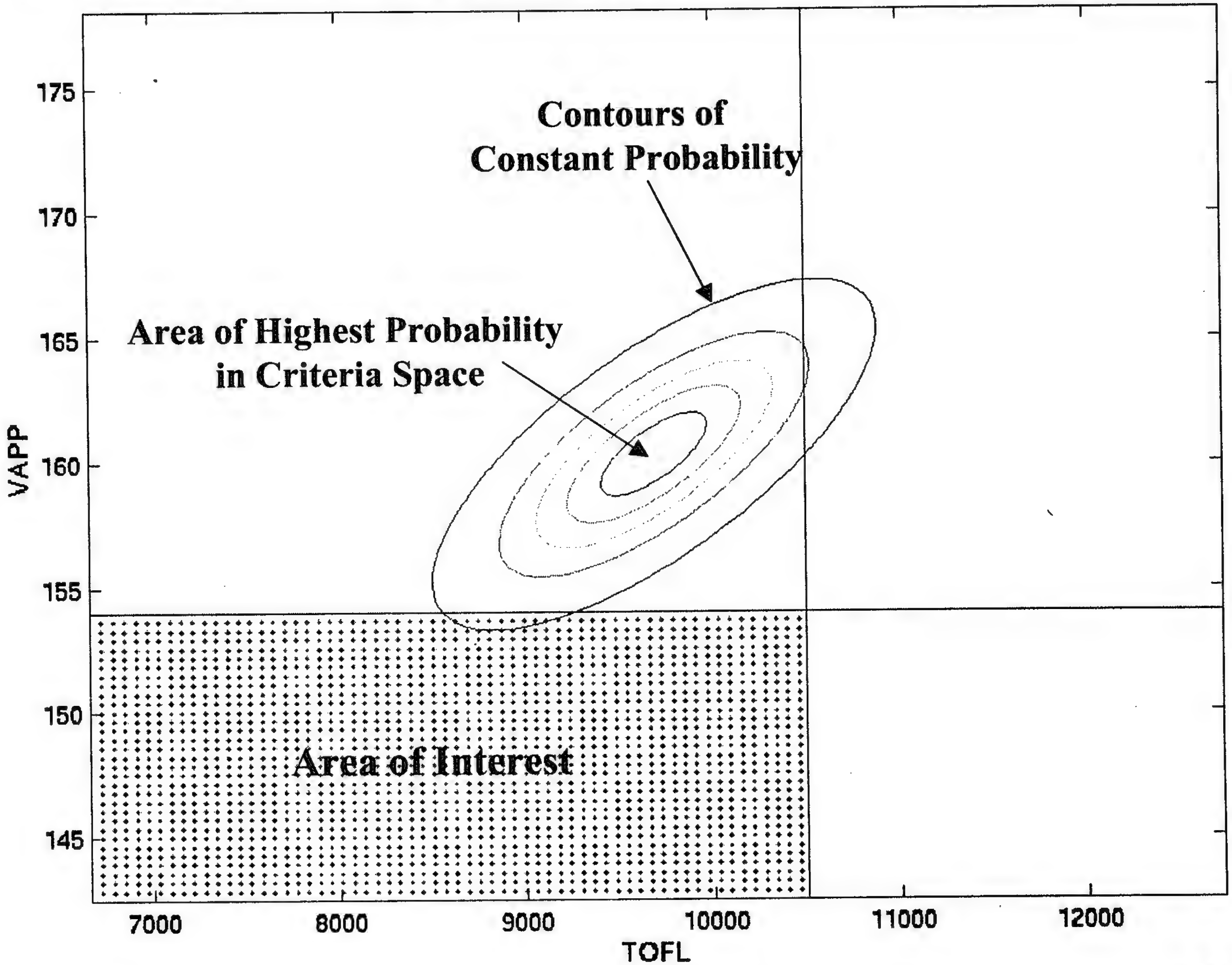
# Joint Probability Density Function - 2D



# Section 3

1. ***Introduction and Research Setting/Summary***

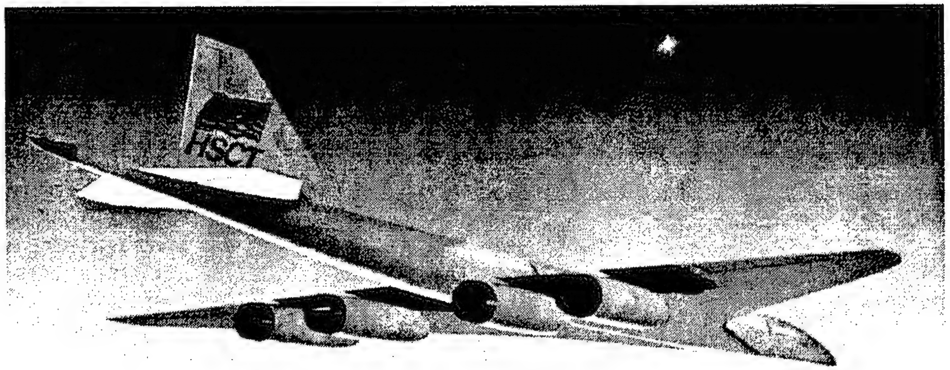
2. ***Overall Technical Approach for Affordable Systems Design***

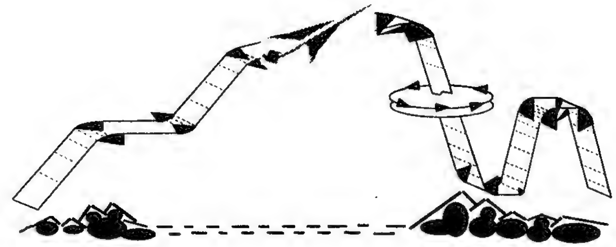
3. ***Methods Implementation and Testbed Applications***
   - *Design Space Exploration (Feasibility Determination for a High Speed Civil Transport)*
   - *TIES Implementation (Technology Selection for an Advanced 150pax Transport)*
   - *Joint Probabilistic Decision Making (JPDM)*
   - *Simultaneous Examination of Requirements and Technologies (F/A-18C Testbed)*

4. ***Key Advancements in Method Components***

5. ***Conclusions/Summary***

# High Speed Civil Transport (HSCT)



- Cruise Mach Number of 2.4
- Range of 5000 nm.
- Carry 300 passengers
- Powered by four engines capable of cruising supersonically without afterburner
- Able to make two round trips to Europe or Pacific Rim in the same amount of time as one trip for a subsonic transport

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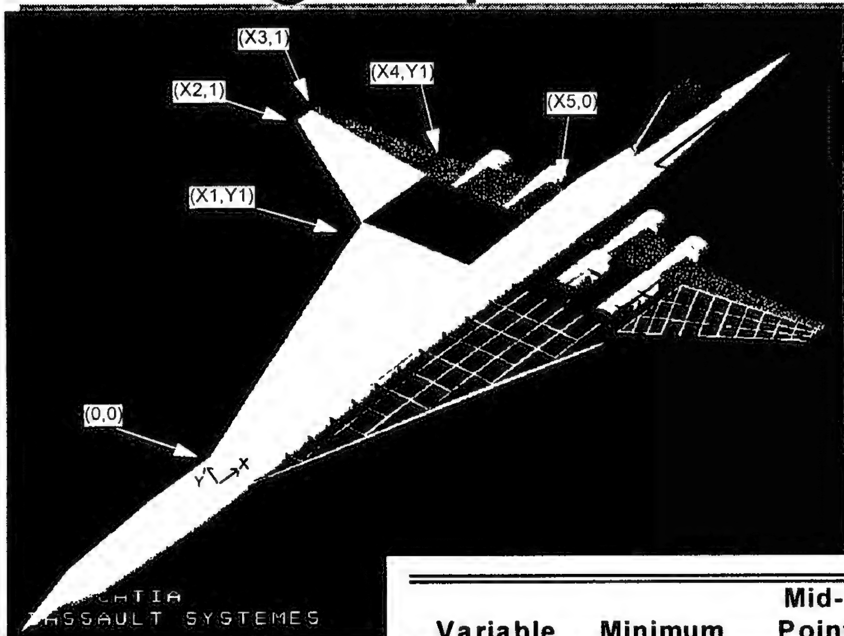
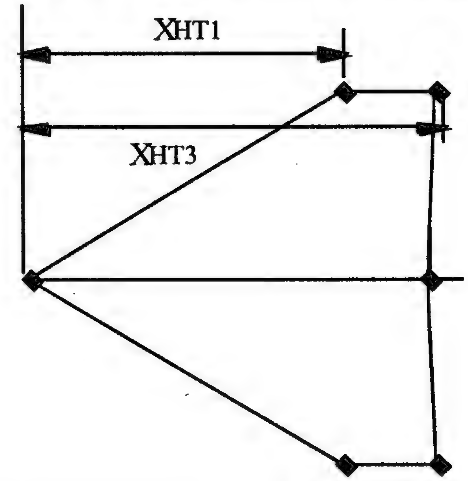
# HSCT Challenges

- Environmental Constraints
  - Engine that is sized to cruise violates FAA noise regulations
  - Nitrogen Oxide emissions harm the ozone layer
- Performance Constraints
  - Poor takeoff and landing characteristics
  - High Mach numbers require special heat-resistant materials
- Economic Constraints
  - Will require a fare premium
  - Will have a high acquisition cost
  - Will require a large initial investment

# High Speed Civil Transport (HSCT)




| Variable | Minimum | Mid-Point | Maximum | Remarks |
|---|---|---|---|---|
| X1 | 1.54 | 1.615 | 1.69 | Kink LE x-location, normalized by wing semi-spa |
| Y1 | 0.44 | 0.51 | 0.58 | Kink LE y-location, normalized by wing semi-spa |
| X2 | 2.10 | 2.23 | 2.36 | Tip LE x-location, normalized by wing semi-span |
| X3 | 2.40 | 2.49 | 2.58 | Tip TE x-location, normalized by wing semi-span |
| X4 | 2.19 | 2.275 | 2.36 | Kink TE x-location, normalized by wing semi-spa |
| X5 | 2.19 | 2.345 | 2.50 | Root Chord, normalized by wing semi-span |
| XWING | 26% | 28% | 31% | wing position, % fuselage length |
| SW | 8500 | 9000 | 9500 | wing ref. area, square feet |
| XTAIL | 82% | 84.7% | 87.4% | horizontal tail position, % fuselage length |
| ST | 875 | 922.5 | 970 | horizontal tail ref. area, square feet |
| XHT1 | 0.95 | 1.18 | 1.20 | normalized by HT semi-span |
| XHT3 | 1.90 | 2.00 | 2.10 | normalized by HT semi-span |
| CG | 56% | 57.5% | 59% | CG, %fuselage |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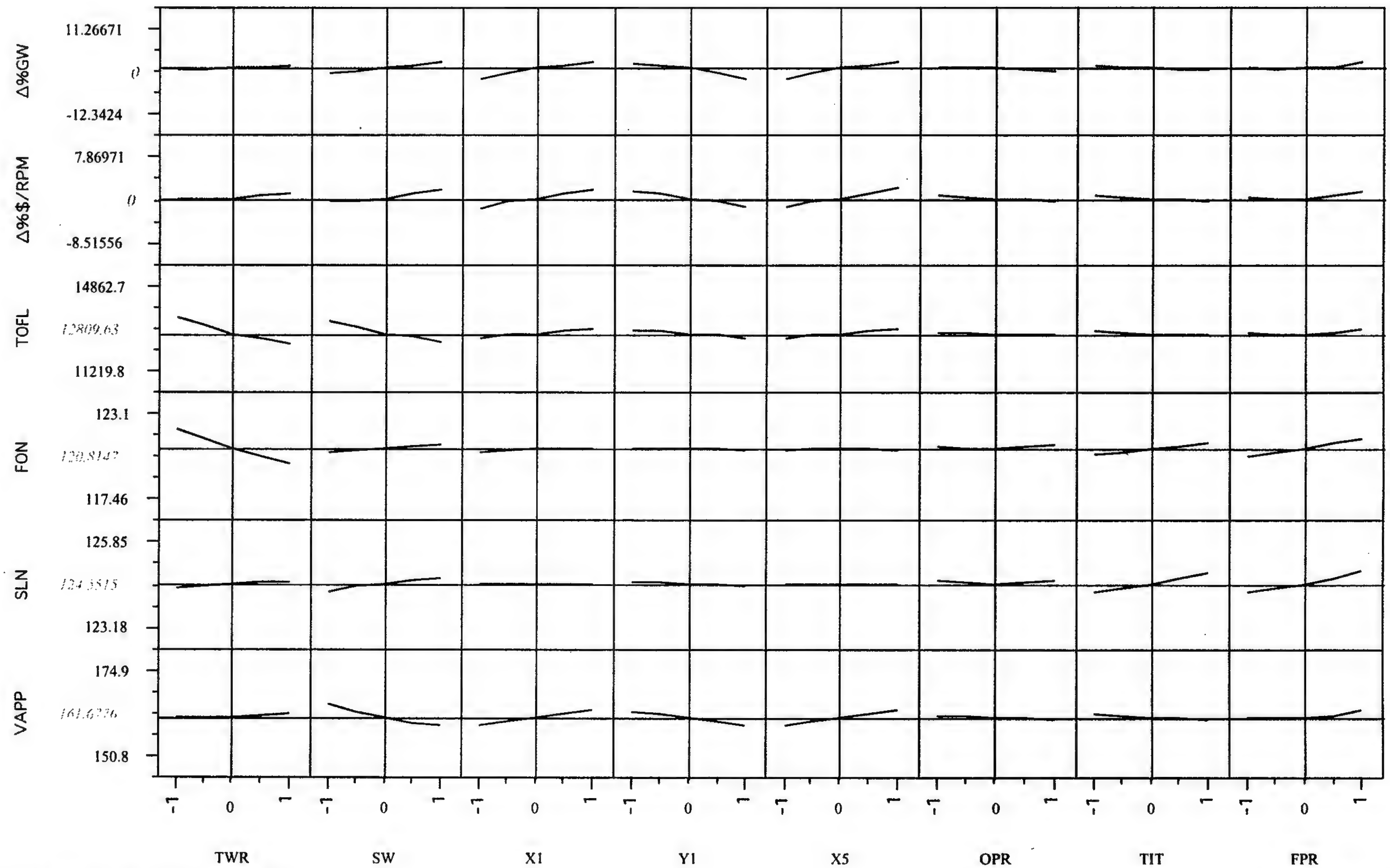
# Prediction Profiles for the HSCT System Level Constraints





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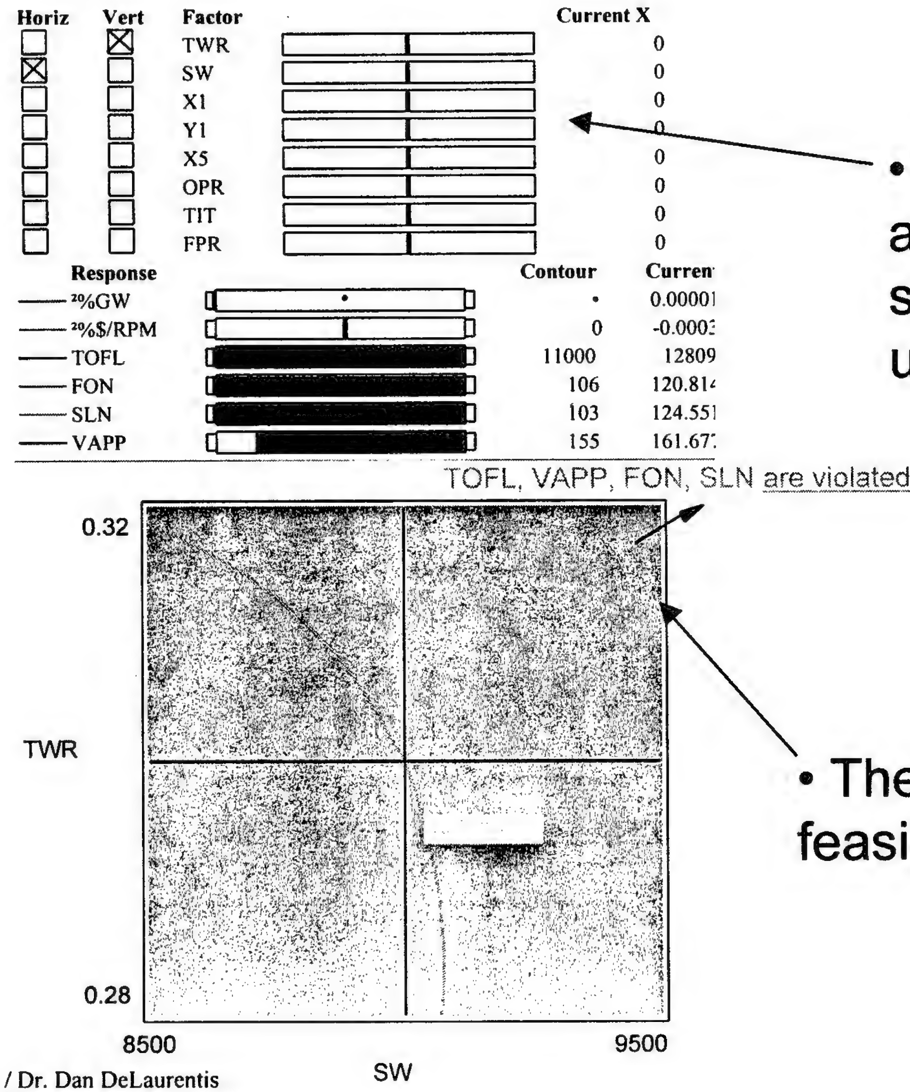
# No Feasible Design Space Due to TOFL, VAPP, FON, and SLN




- The slide bars can be used to adjust the design variable settings, and the design plot is updated in real time.
- The design space plot shows no feasible space.

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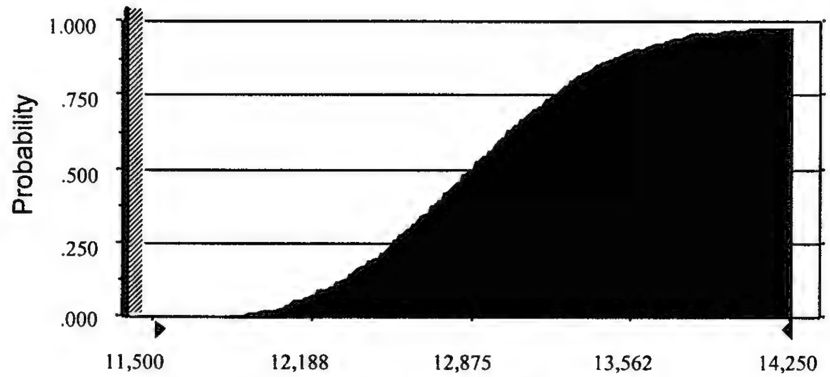
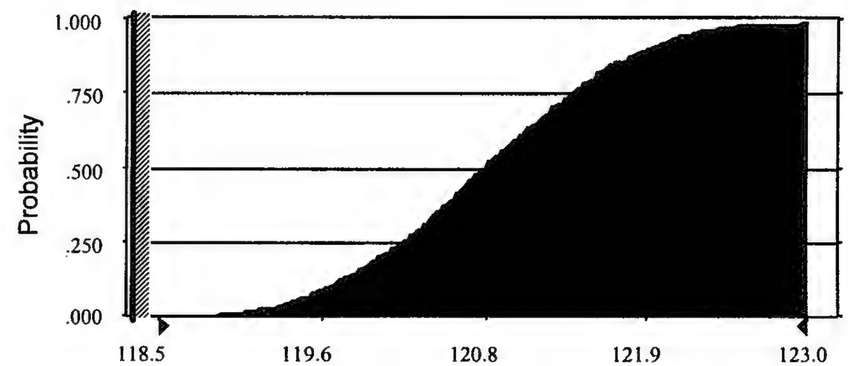
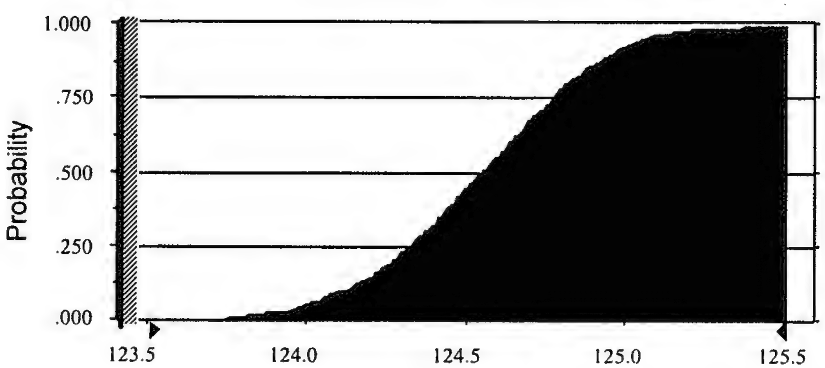
# CDFs for the Four Constraints,

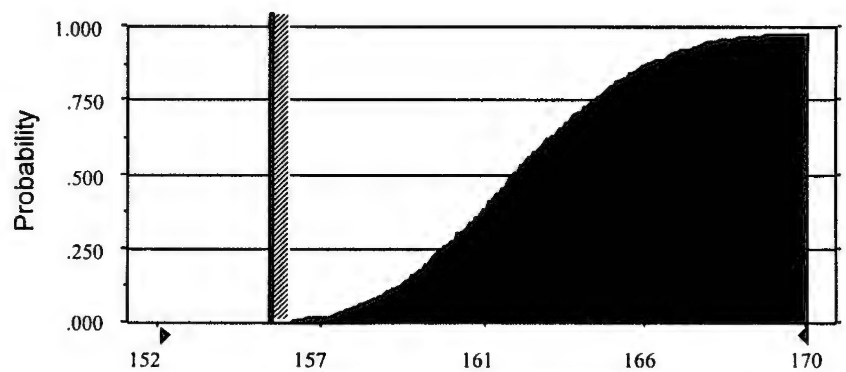
## from Monte Carlo Simulation (5,000 samples)

## All constraints violated throughout initial design space





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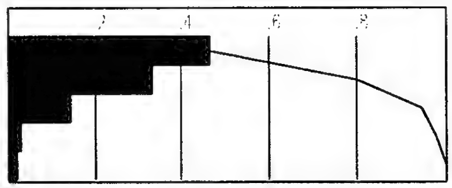
# Pareto Charts: Mission Requirements Sensitivities

## $/RPM

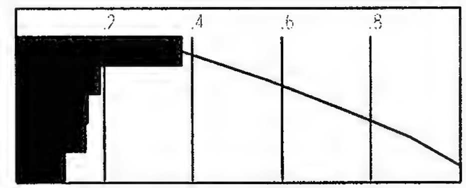
Average Required Yield per Revenue Passenger Mile

| Term | Orthog Estimate |
|---|---|
| PAX | -0.0048359 |
| %SubsMiss | 0.00348035 |
| Des-Range | 0.00151828 |
| S-Wing | 0.00032233 |
| 1/W-Ratio | 0.00024368 |



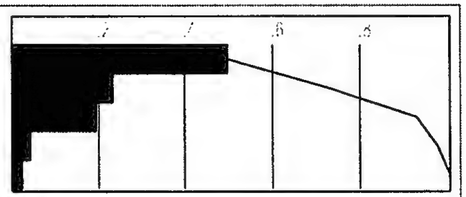

## $-Acquisition Price

| Term | Orthog Estimate |
|---|---|
| Des-Range | 3.5722524 |
| PAX | 1.8383051 |
| %SubsMiss | 1.5712922 |
| 1/W-Ratio | 1.4931703 |
| S-Wing | 1.0737944 |



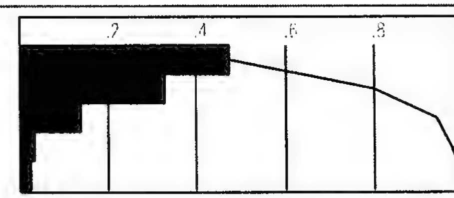

## Gross Weight

| Term | Orthog Estimate |
|---|---|
| Des-Range | 23175.393 |
| %SubsMiss | 10861.366 |
| PAX | 9171.229 |
| S-Wing | 2168.852 |
| 1/W-Ratio | 1176.909 |



## Direct Operating Costs

| Term | Orthog Estimate |
|---|---|
| PAX | -0.0025538 |
| %SubsMiss | 0.00177578 |
| Des-Range | 0.00075366 |
| S-Wing | 0.00017851 |
| 1/W Ratio | 0.00014310 |

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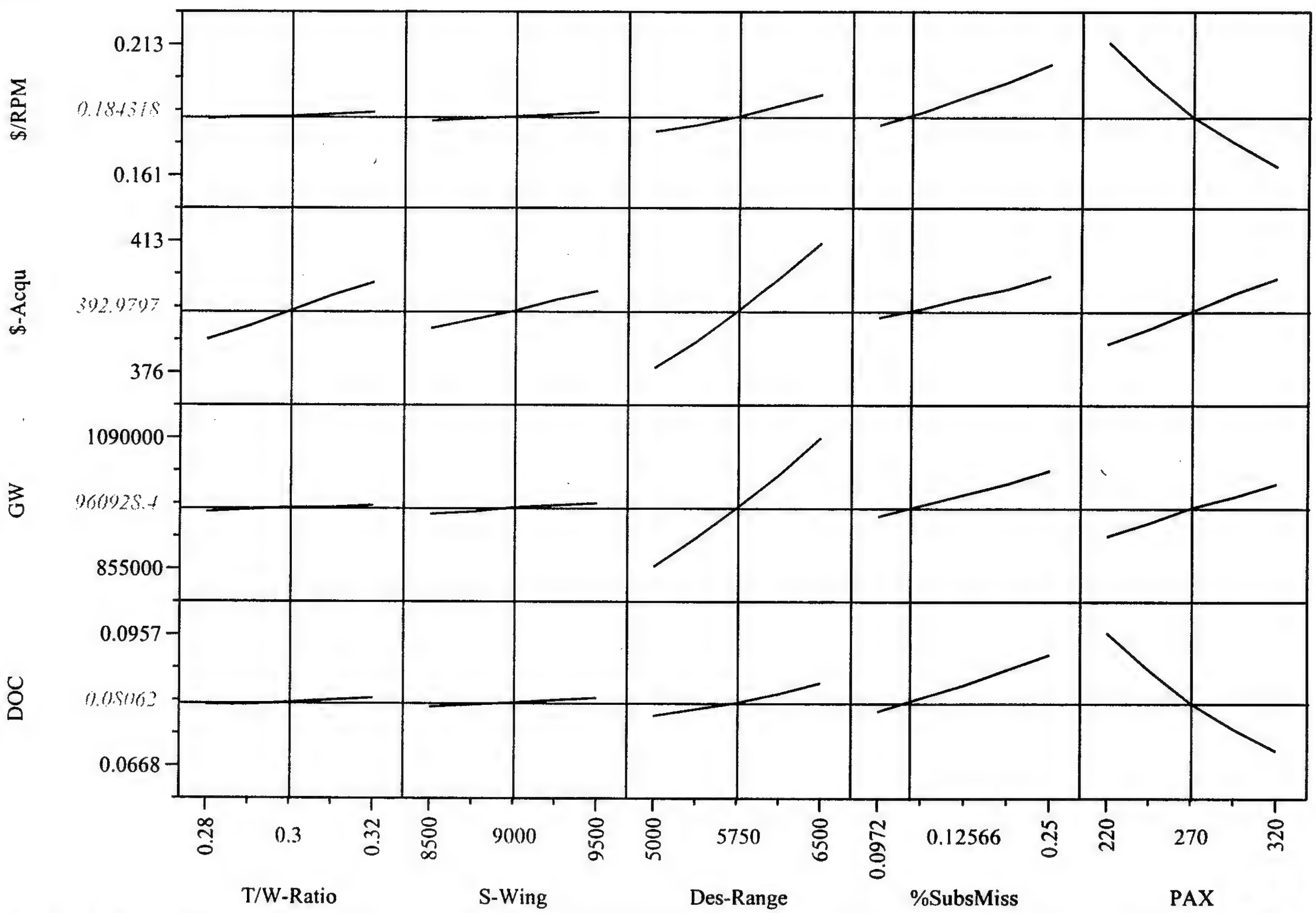
# Mission Requirements Sensitivities





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# Feasibility and Viability Assessment

- If design space is not technically feasible or economically viable, the decision maker has 3 options:

1) Open design variable ranges further

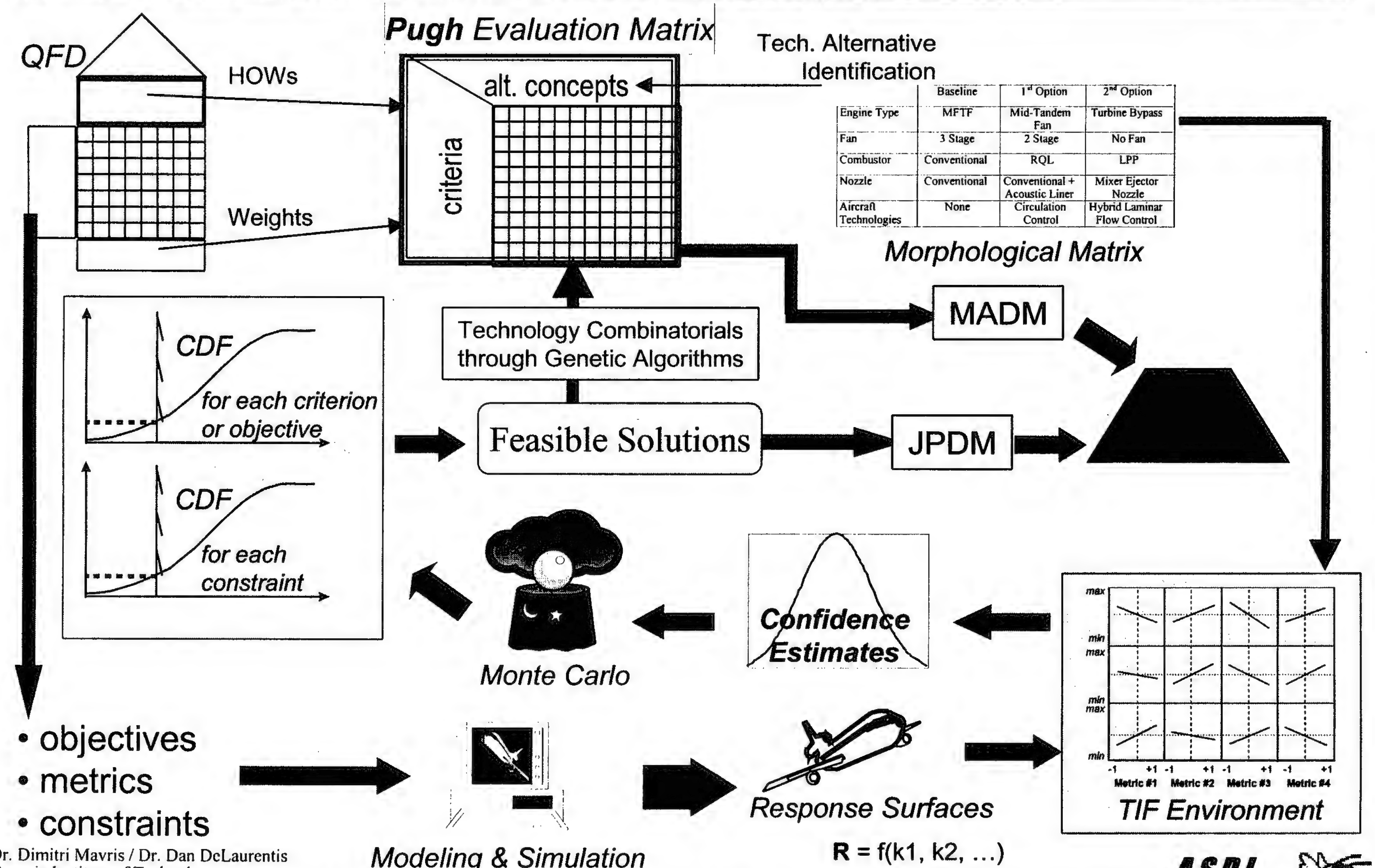
   *- Design Space Exploration yielded no improvement*

2) Relax constraints

   *- Non-negotiable in this case*

3) Infuse new technologies !!!

# Technology Identification Evaluation Selection (TIES)




| | Baseline | 1st Option | 2nd Option |
|---|---|---|---|
| Engine Type | MFTF | Mid-Tandem Fan | Turbine Bypass |
| Fan | 3 Stage | 2 Stage | No Fan |
| Combustor | Conventional | RQL | LPP |
| Nozzle | Conventional | Conventional + Acoustic Liner | Mixer Ejector Nozzle |
| Aircraft Technologies | None | Circulation Control | Hybrid Laminar Flow Control |

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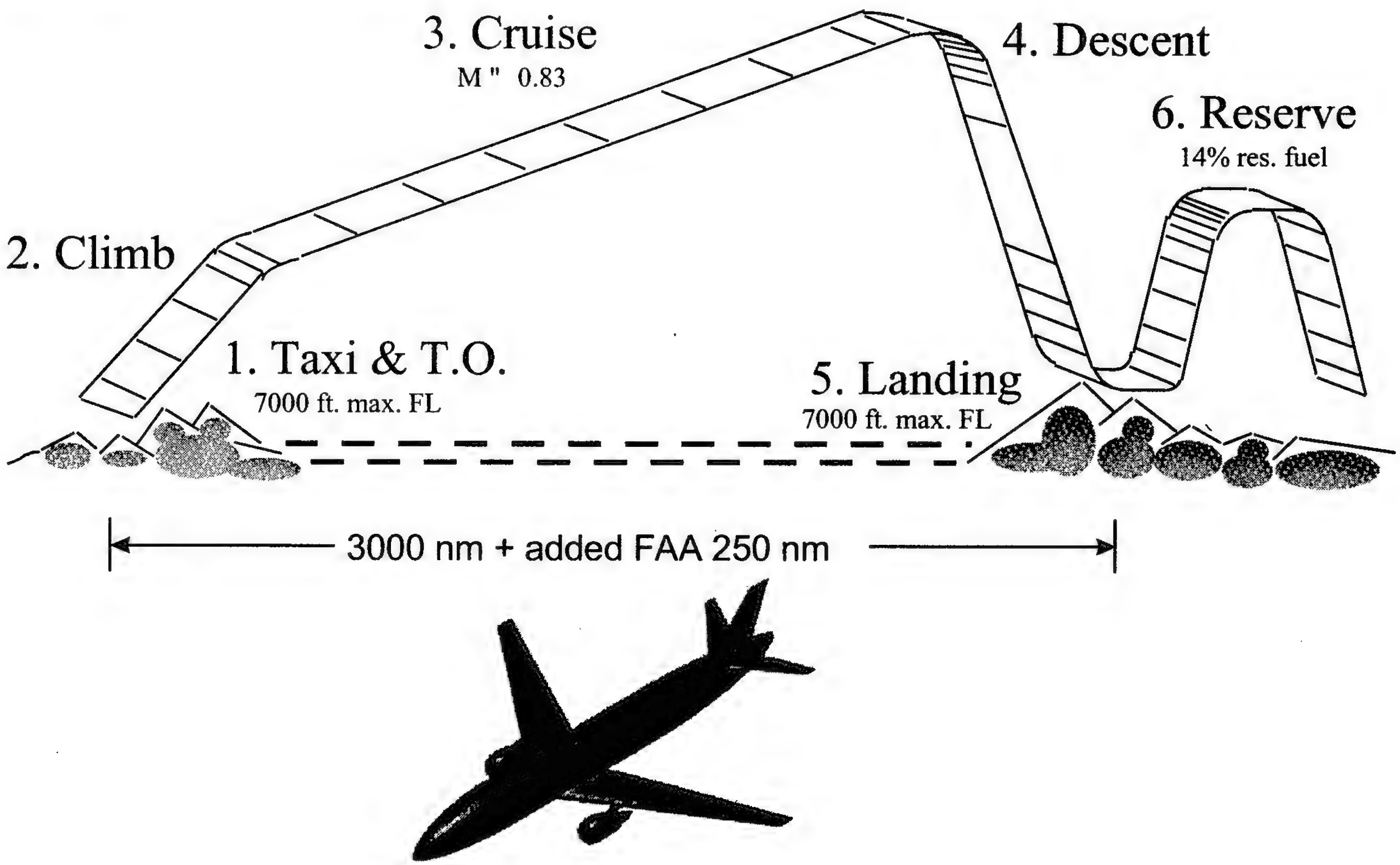
# Example Problem

- The implementation of the feasibility aspect of TIES has been performed on various vehicles
- The down-select of the specific technologies is the new dimension of the TIES method and will be applied for the example problem
- The proof of concept is performed on a 150 passenger, medium-range, intra-continental commercial transport and the technologies are evaluated deterministically
- See SAE Paper 98-5547 for the feasibility assessment, SAE Paper 98-5576 for the TIF, and AIAA 99-0183 for the joint probability decision making

# Problem Definition: *150 passenger concept*

## Medium Range, Intra-continental Commercial Vehicle

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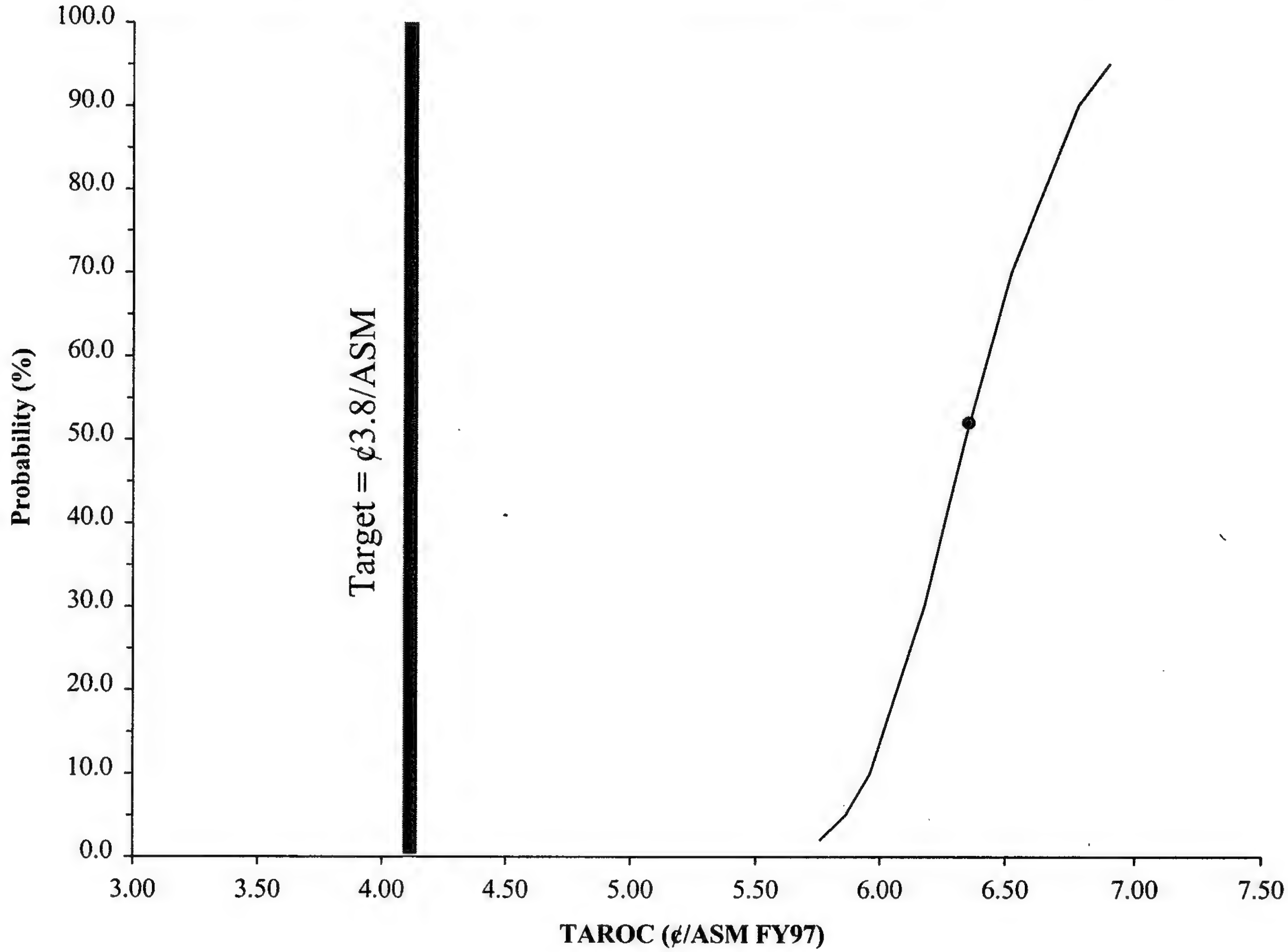
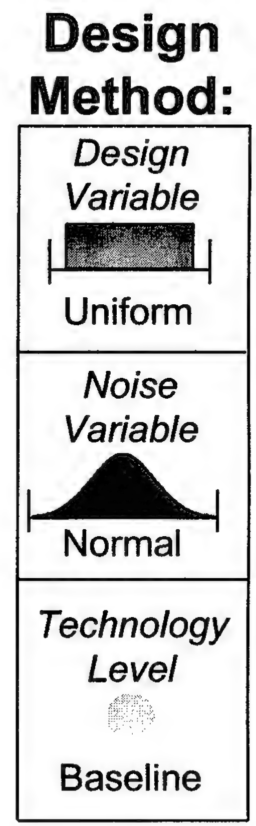
# Problem Definition: *Quantitative System Level Metrics*

| Parameter | Baseline Value | Target | Target Value | Units |
|---|---|---|---|---|
| Weights and Performance | | | | |
| $V_{app}$ | 115.7 | *minimize* | ~ | kts |
| Fuel Burn | 44267 | -48% | 23019 | lbs |
| Landing FL | 4944 | -21% | 3906 | ft |
| OEW | 73850 | -40% | 44310 | lbs |
| TOFL | 5970 | -21% | 4706 | ft |
| TOGW | 149618 | -31% | 103236 | lbs |
| Economics | | | | |
| DOC+I | 5.22 | -42% | 3.03 | ¢/ASM |
| TAROC | 6.03 | -37% | 3.80 | ¢/ASM |

# Viability Assessment: *TAROC*

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# Technology Identification

## *Compatibility Matrix*

**Compatibility Matrix**
**(1: compatible, 0: incompatible)**

| | Composite Wing | Composite Fuselage | Aircraft Morphing | Natural Laminar Flow Control | Maneuver Load Alleviation | AST Engine Concept | Integrally, Stiffened Aluminum Airframe Structures (wing) | HLFC | IHPTET Engines |
|---|---|---|---|---|---|---|---|---|---|
| Composite Wing | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| Composite Fuselage | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Aircraft Morphing | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Natural Laminar Flow Control | | | | 1 | 1 | 1 | 1 | 0 | 1 |
| Maneuver Load Alleviation | | | | | 1 | 1 | 1 | 1 | 1 |
| AST Engine Concept | | | | | | 1 | 1 | 1 | 0 |
| Integrally, Stiffened Aluminum Airframe Structures (wing) | | | | | | | 1 | 0 | 1 |
| HLFC | | | | | | | | 1 | 1 |
| IHPTET Engines | | | | | | | | | 1 |

Symmetric Matrix

# Technology Identification

## *TIM: Technology Impact Matrix*

| Technical K_Factor Elements / Technical K_Factor Vector | Composite Wing | Composite Fuselage | Aircraft Morphing | Natural Laminar Flow Control | Maneuver Load Alleviation | AST Engine Concept | Integrally, Stiffened Aluminum Airframe Structures (wing) | HLFC | IHPTET Engines |
|---|---|---|---|---|---|---|---|---|---|
| Wing area | ~ | ~ | | ~ | +18% | ~ | ~ | ~ | ~ |
| Vertical tail area | ~ | ~ | ~ | ~ | -40% | ~ | ~ | ~ | ~ |
| Horizontal tail area | ~ | ~ | ~ | ~ | -36% | ~ | ~ | ~ | ~ |
| Drag | -2% | -2% | -3% | -5% | -3% | ~ | ~ | -10% | ~ |
| Subsonic fuel flow | ~ | -0.5% | -1.5% | ~ | ~ | -10% | ~ | +1% | -5% |
| Wing weight | -15% | ~ | -3% | ~ | ~ | ~ | -15% | +4% | ~ |
| Fuselage weight | ~ | -25% | -2% | ~ | ~ | ~ | ~ | ~ | ~ |
| Electrical weight | ~ | ~ | ~ | ~ | +5% | +3% | ~ | +2% | ~ |
| Engine weight | ~ | ~ | ~ | ~ | ~ | -30% | ~ | +0.5% | -20% |
| Hydraulics weight | ~ | ~ | ~ | ~ | -10% | ~ | ~ | ~ | ~ |
| AL wing structure manufacturing costs | ~ | ~ | ~ | ~ | ~ | ~ | -2.5% | ~ | ~ |
| O&S | +2% | +2% | ~ | ~ | ~ | -3% | -2% | +3% | -3% |
| RDT&E | +2% | +2% | +2% | +2% | +3% | -4% | ~ | +4% | +3% |
| Production costs | +10% | +10% | -3% | +1% | ~ | -3% | ~ | +1% | ~ |
| Utilization | -2% | -2% | ~ | ~ | ~ | +3% | +2% | -2% | +2% |

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# Technology Impact Matrix

- Potential system and subsystem level benefits and penalties associated with the technologies identified in the Morphological and Compatibility Matrices are established via expert questionnaires, physics-based modeling, or literature reviews
- In general, benefits and penalties are probabilistic (possibly stochastic) in nature
- Technology impact can be simulated in the TIF environment through technology "k_factor" vectors and summarized in a TIM

| "K" Factor Elements | Technical "K" Factor Vector | T1 | T2 | T3 |
|---|---|---|---|---|
| | k factor 1 | +4% | ~ | -10% |
| | k factor 2 | ~ | -3% | ~ |
| | k factor 3 | -1% | ~ | -2% |
| | k factor 4 | -2% | -2% | +3% |

where a technology can be represented as:

$$T_i = \vec{k}_i = \left\{ \begin{matrix} \mu_{i,1}, \sigma_{i,1} \\ \mu_{i,2}, \sigma_{i,2} \\ \cdots \\ \mu_{i,n}, \sigma_{i,n} \end{matrix} , TRL_i \right\}$$

where:
"i" : specific technology
"n": number of k_factors
"μ": mean of the k_factor
"σ": variance of the k_factor
"TRL": technology readiness level

# Technology Impact Forecasting

***"k" Factor RSE Generation***

| Technical Metric "K" Factor Elements | Non-dimensional impact Min (%) | Max (%) |
|---|---|---|
| Wing area | 0 | 18 |
| Vertical tail area | -40 | 0 |
| Horizontal tail area | -36 | 0 |
| Drag | -25 | 0 |
| Subsonic fuel flow | -17 | 1 |
| Wing weight | -33 | 4 |
| Fuselage weight | -27 | 0 |
| Electrical weight | 0 | 10 |
| Engine weight | -50 | 0.5 |
| Hydraulics weight | -10 | 0 |
| AL wing structure manufacturing costs | -2.5 | 0 |
| O&S | -8 | 7 |
| RDT&E | -4 | 18 |
| Production costs | -6 | 22 |
| Utilization | -6 | 7 |

Constraint/Objective = $f(k_1, k_2, \ldots, k_n)$ as obtained from a Design of Experiments to obtain a second order equation of the form:

$$R = b_o + \sum_{i=1}^{k} b_i k_i + \sum_{i=1}^{k} b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} k_i k_j$$

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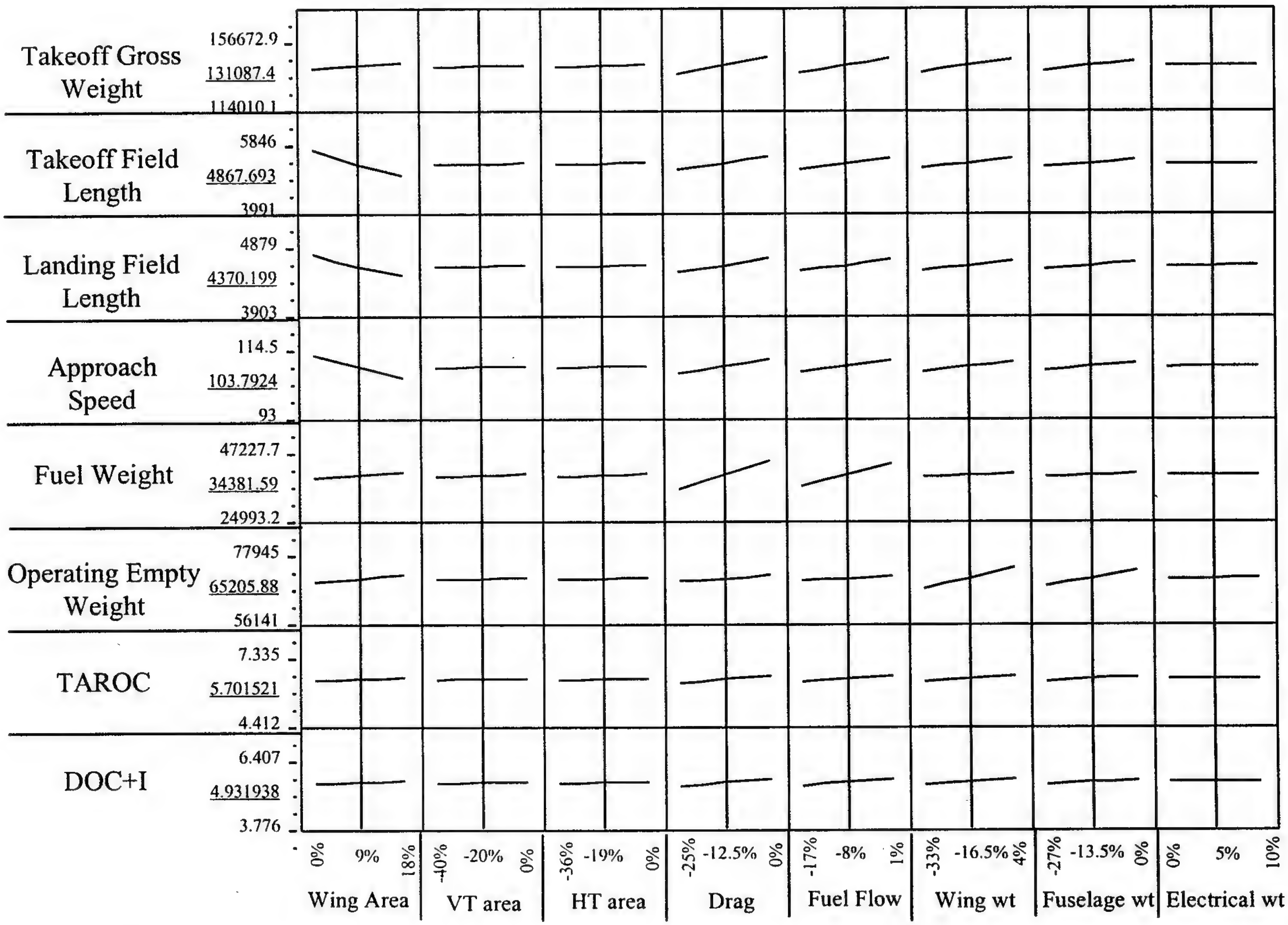
# TIF Environment (1)

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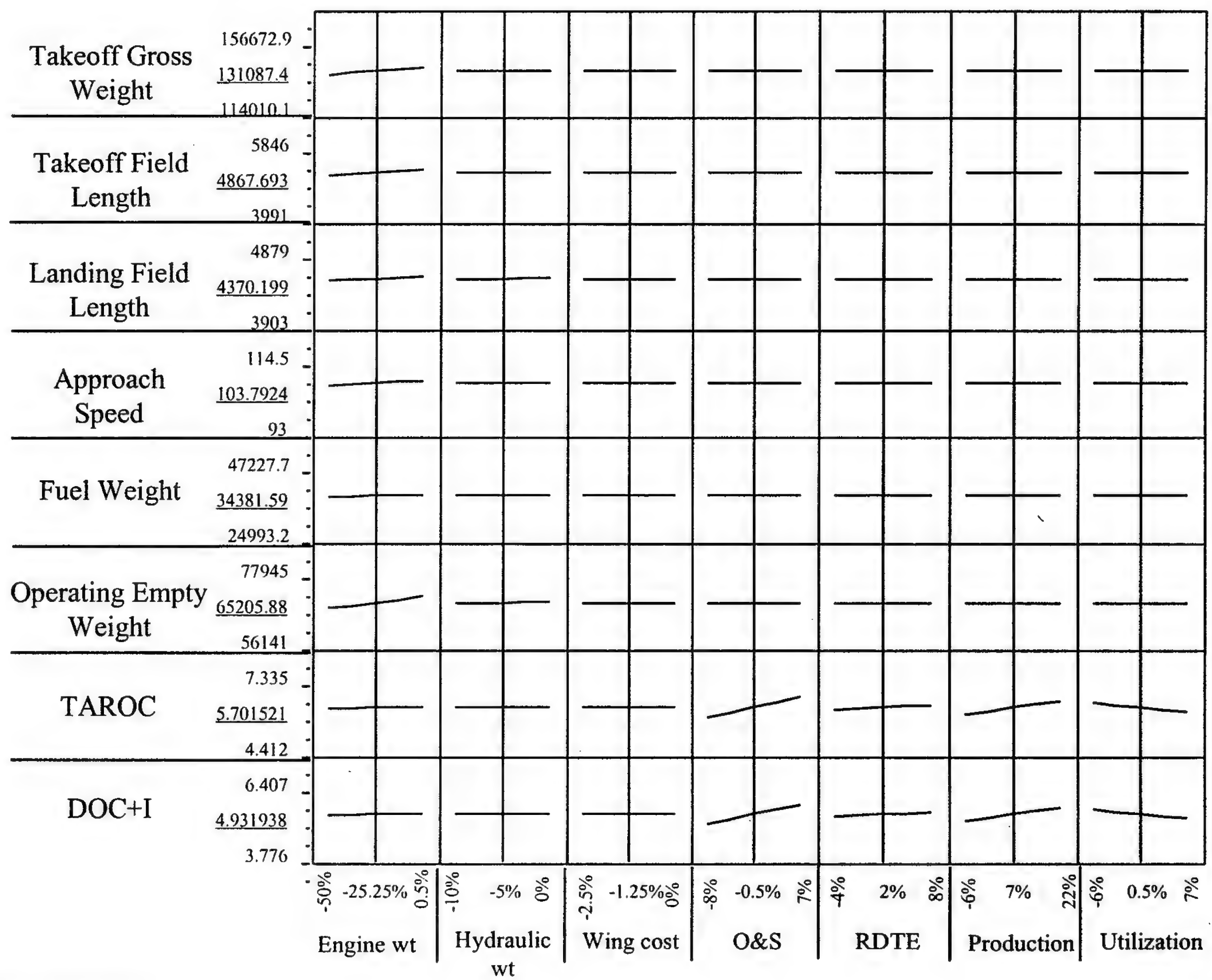
# TIF Environment (2)

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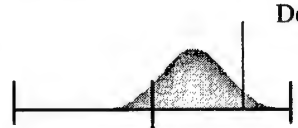
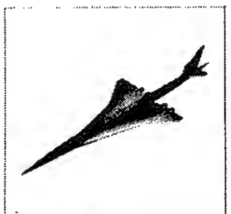
# Technology Mapping

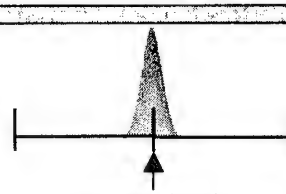
Infuse Tech #1 $\Rightarrow$ $f(\vec{k}_1)=\begin{Bmatrix}\mu_{1,1},\sigma_{1,1}\\ \mu_{1,j},\sigma_{1,j},TRL=3\\ \mu_{1,n},\sigma_{1,n}\end{Bmatrix}$ L/D




$\Rightarrow f\begin{pmatrix}disciplinary\\ metrics\end{pmatrix}_1 \Rightarrow \vec{A}_1=\begin{Bmatrix}Performance_1\\ Geometry\\ Economic_1\end{Bmatrix}$

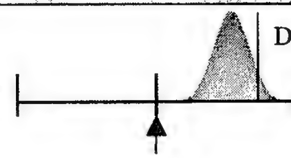


$f(\vec{k}_{conv})=\begin{Bmatrix}\mu_{conv,1},\sigma_{conv,1}\\ \mu_{conv,j},\sigma_{conv,j},TRL=9\\ \mu_{conv,n},\sigma_{conv,n}\end{Bmatrix}$ L/D

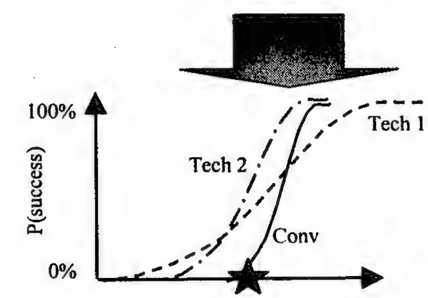



$\Rightarrow f\begin{pmatrix}disciplinary\\ metrics\end{pmatrix} \Rightarrow \vec{A}=\begin{Bmatrix}Performance\\ Geometry\\ Economic\end{Bmatrix}$

Infuse Tech #2 $\Rightarrow$ $f(\vec{k}_2)=\begin{Bmatrix}\mu_{2,1},\sigma_{2,1}\\ \mu_{2,j},\sigma_{2,j},TRL=6\\ \mu_{2,n},\sigma_{2,n}\end{Bmatrix}$ L/D




$\Rightarrow f\begin{pmatrix}disciplinary\\ metrics\end{pmatrix}_2 \Rightarrow \vec{A}_2=\begin{Bmatrix}Performance_2\\ Geometry\\ Economic_2\end{Bmatrix}$





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# Technology Evaluation

- The identification of the proper mix of technologies for a given system is dominated by the curse of dimensionality
- *Curse of Dimensionality*: the search for the proper mix of technologies which will "best" satisfy the system level metrics or attributes can be enormous
  - $2^n$ combinations, where "n" is the number of technologies
    - 9 technologies implies 512 combinations
    - *20 technologies implies 1,048,576 combinations*
  - Computational expense of the analysis is the primary driver
    - *manageable*: full factorial investigation
    - *unmanageable*: genetic algorithm investigation

# Technology Evaluation: *Full Factorial Investigation*

| Case | T1 | T2 | T3 | ........ | T9 | Metric $_1$ | Metric $_2$ | ........ | Metric $_n$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | ........ | -1 | # | # | ........ | # |
| 2 | -1 | 1 | -1 | ........ | 1 | # | # | ........ | # |
| 3 | -1 | -1 | -1 | ........ | 1 | # | # | ........ | # |
| $2^n$ | 1 | 1 | 1 | ........ | 1 | # | # | ........ | # |

evaluations of Metric RSEs if all technologies are compatible

"1" implies technology applied
"-1" implies no technology

Metric value is determined from the RSEs

*Consider an alternative with aircraft morphing (T3) and IHPTET engines (T9)*

Recall:

$$\vec{k}_i = \begin{Bmatrix} k\_1 \\ k\_2 \\ k\_3 \\ k\_4 \\ k\_5 \\ k\_6 \\ k\_7 \\ k\_8 \\ k\_9 \\ k\_10 \\ k\_11 \\ k\_12 \\ k\_13 \\ k\_14 \\ k\_15 \end{Bmatrix}$$

**Alternative with: T3**

$$\vec{k}_3 = \begin{Bmatrix} \sim \\ \sim \\ \sim \\ -3\% \\ -1.5\% \\ -3\% \\ -2\% \\ \sim \\ \sim \\ \sim \\ \sim \\ \sim \\ +2\% \\ -3\% \\ \sim \end{Bmatrix}$$

**Alternative with: T9**

$$\vec{k}_9 = \begin{Bmatrix} \sim \\ \sim \\ \sim \\ \sim \\ -5\% \\ \sim \\ \sim \\ \sim \\ -20\% \\ \sim \\ \sim \\ -3\% \\ +3\% \\ \sim \\ +2\% \end{Bmatrix}$$

**Alternative with: T3+T9**

$$\vec{k}_{3+9} = \begin{Bmatrix} \sim \\ \sim \\ \sim \\ -3\% \\ -6.5\% \\ -3\% \\ -2\% \\ \sim \\ -20\% \\ \sim \\ \sim \\ -3\% \\ +5\% \\ -3\% \\ +2\% \end{Bmatrix}$$

Metric RSE = $f(\vec{k}_{3+9})$

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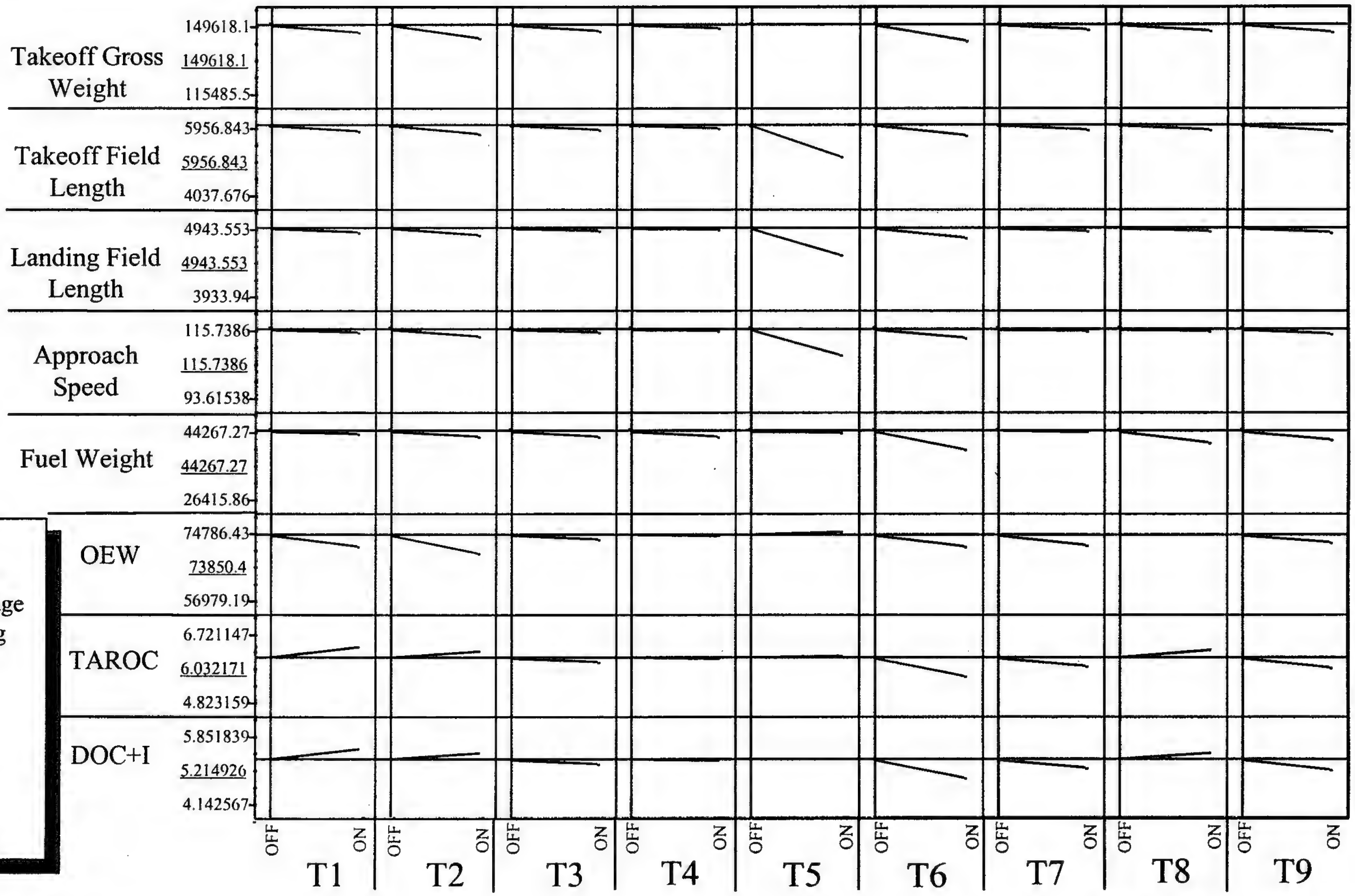
# Full Factorial Technology Evaluation




**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines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# Technology Resource Allocation

- Based on the TIES method results, the most influential individual technologies can be compared to the baseline metrics in an efficient and rapid manner

- The most influential technologies can be identified so as to optimize program resource allocation for technology research and development to overcome constraints or meet objectives

# Technology Resource Allocation

## *TOGW*

**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
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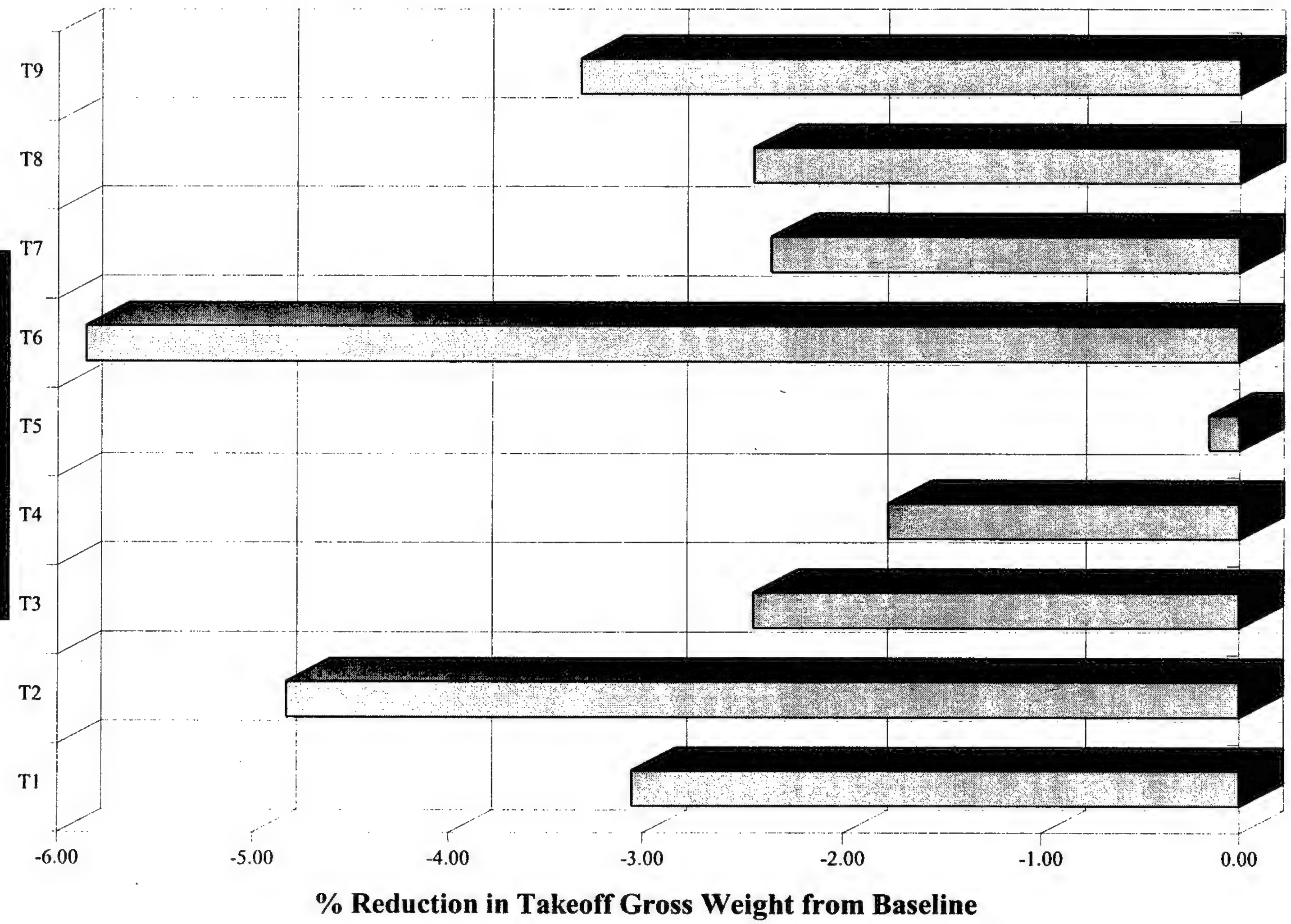


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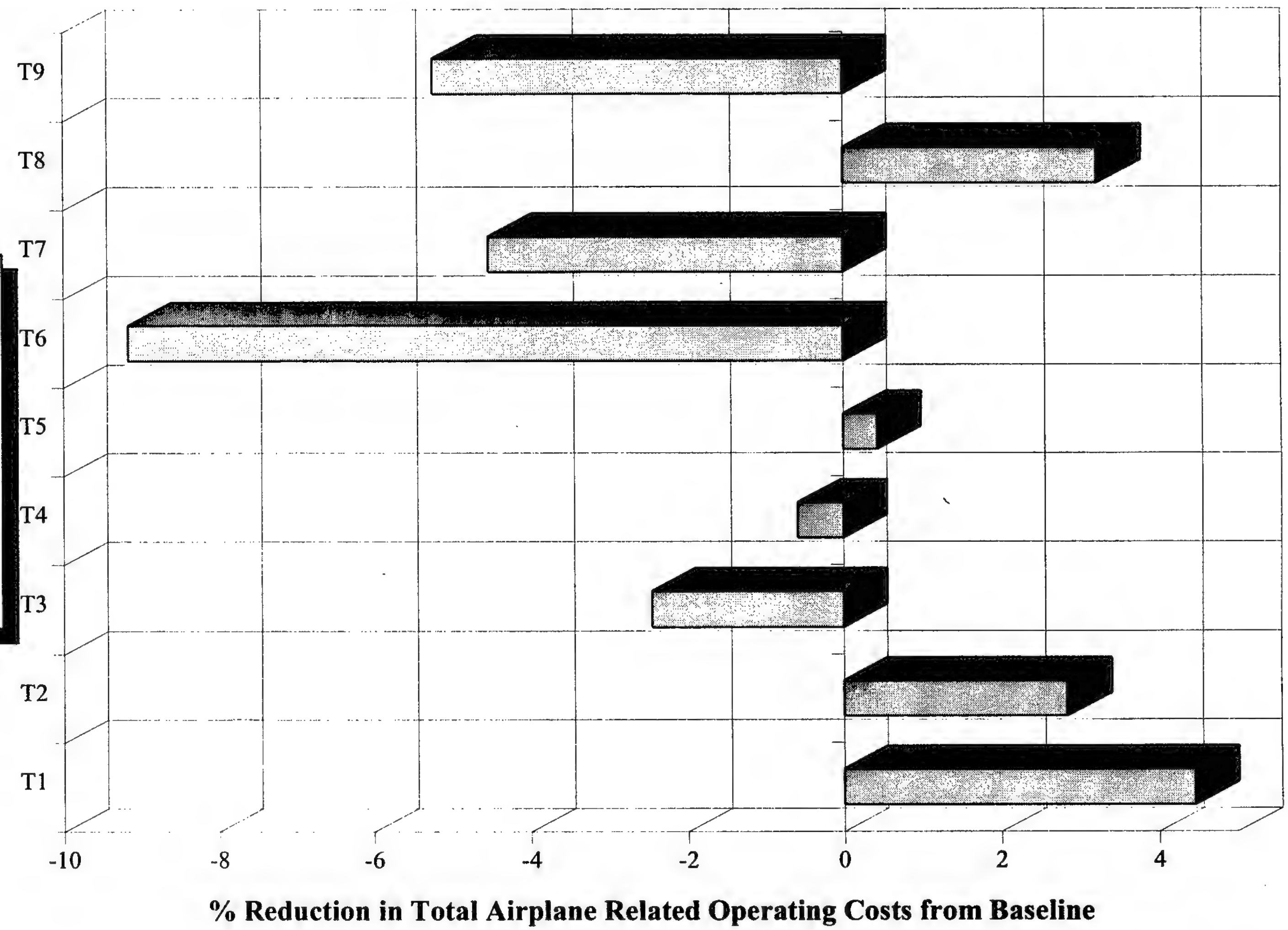
# Technology Resource Allocation

## *TAROC*

**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines

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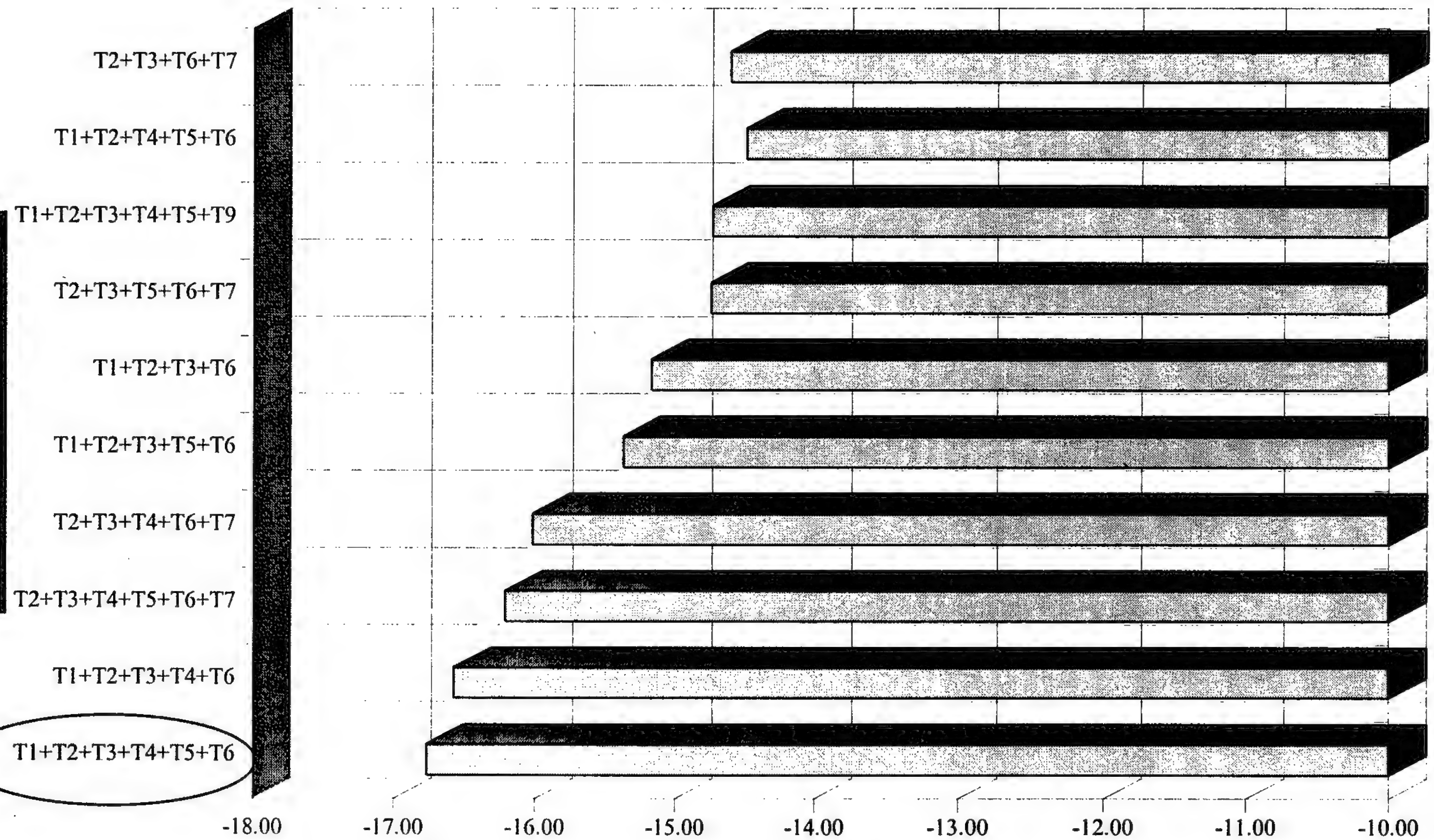
# Top Alternatives

## *Evaluation Based on Minimum TOGW*

**Technologies:**
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines




"Best" Alternative
for Minimum TOGW

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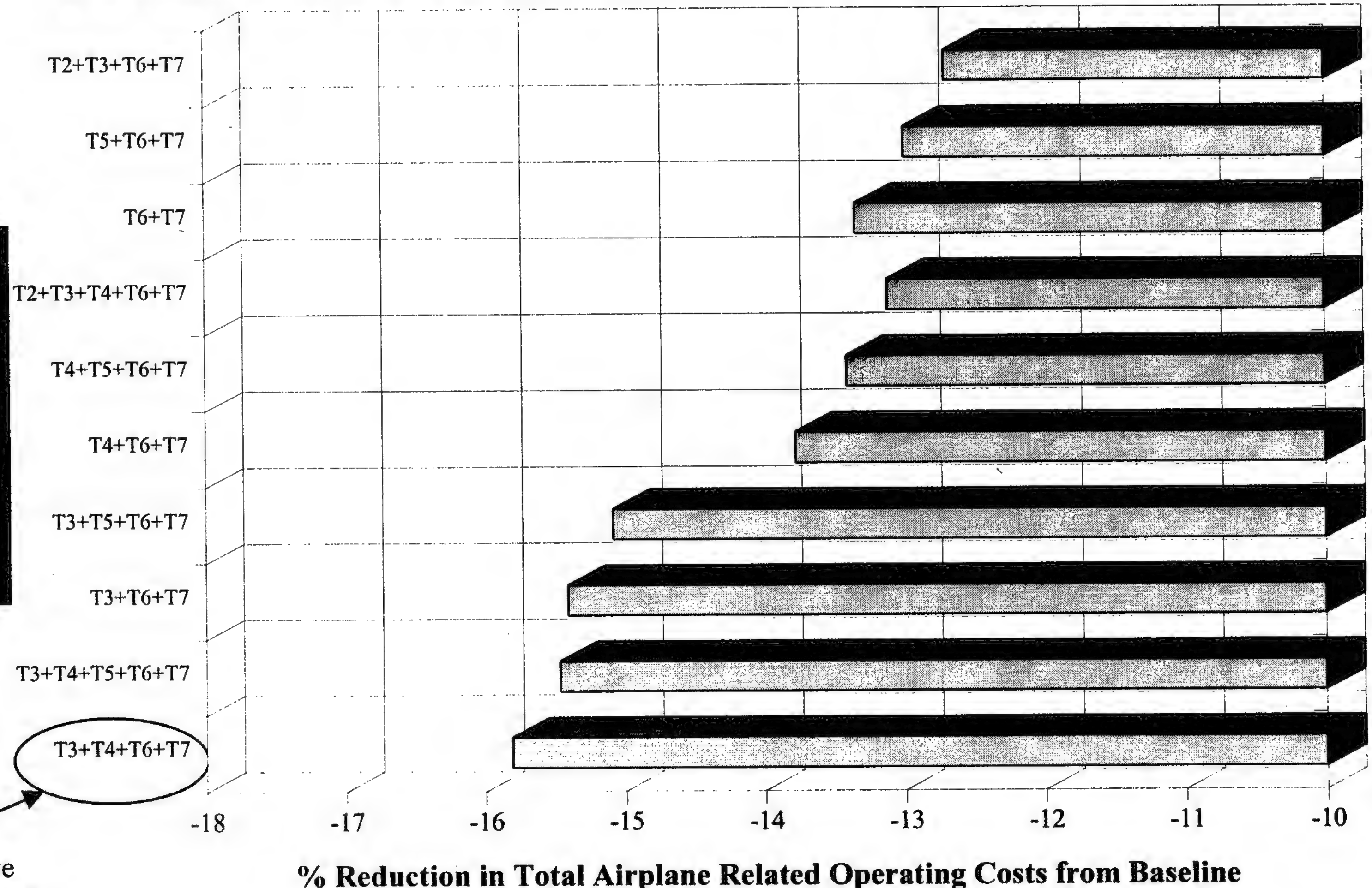
# Top Alternatives

## *Evaluation Based on Minimum TAROC*

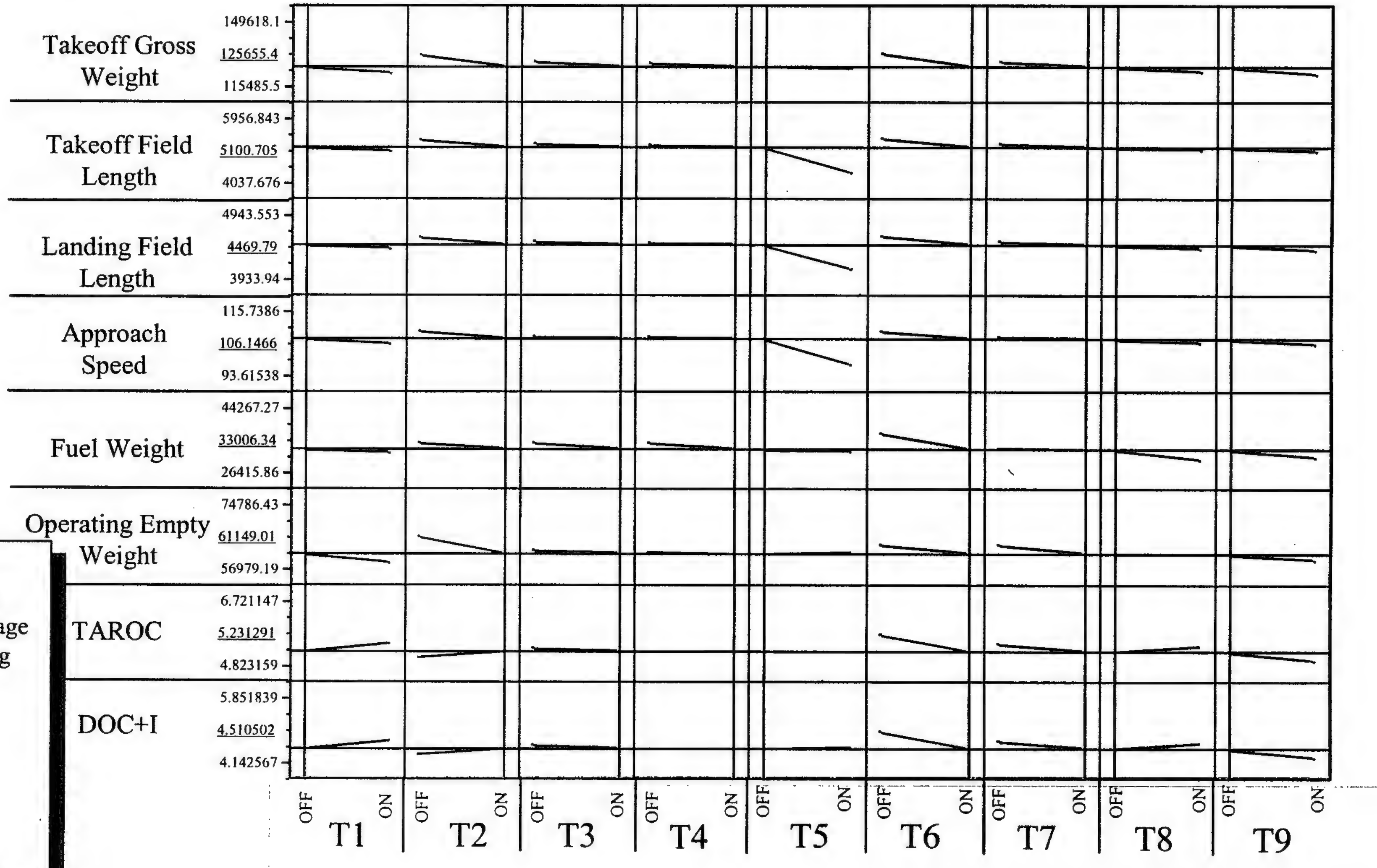
**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines




"Best" Alternative
for Minimum TAROC

# "Best" Alternative

***Evaluation Based on Minimum TAROC and TOGW***




**Technologies**:
T1: Composite Wing
T2: Composite Fuselage
T3: Aircraft Morphing
T4: NLFC
T5: Maneuver Load
T6: AST Concept Engines
T7: ISSA Structures
T8: HLFC
T9: IHPTET Engines

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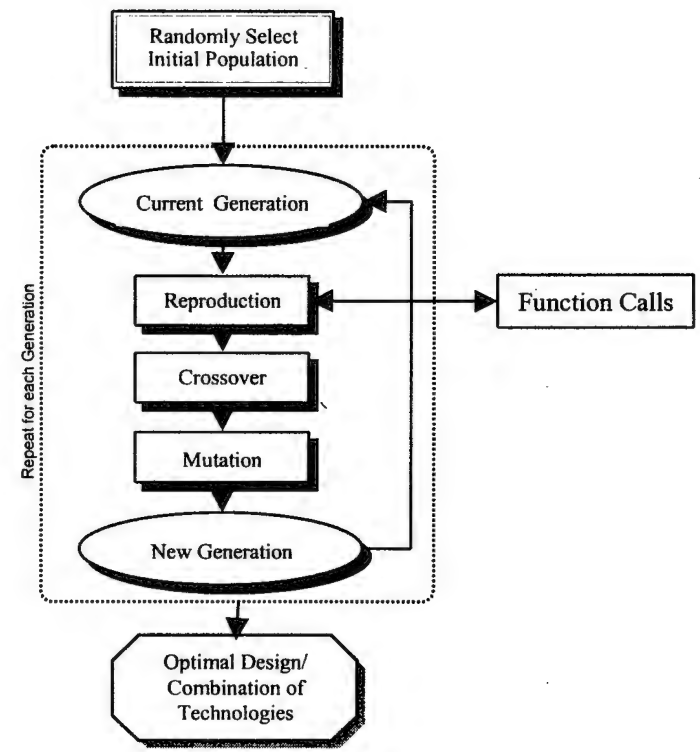
# Genetic Algorithm Investigation

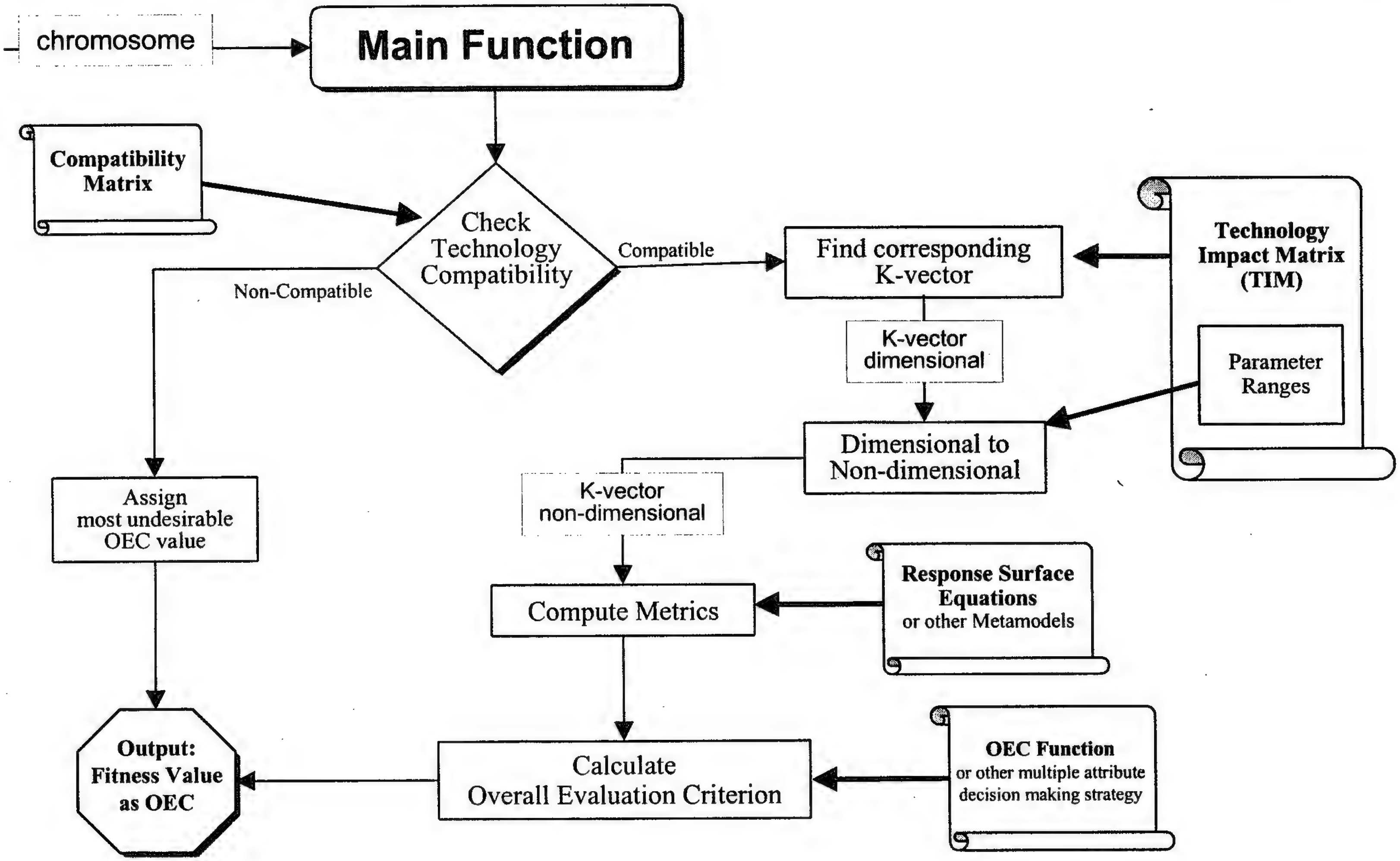
- A simple deterministic proof of concept was performed with a genetic algorithm (GA) for the equal weighting OEC
- The identical mix of technologies from the TOPSIS technique was obtained
- Future work will focus on application of the GA method with probabilistic k_factor vectors and multi-attribute and conflicting objectives

# Genetic Algorithm Implementation

- Identify:
  - Number of Technologies
  - Number of Subsystems
  - Number of Metric Responses
- Specify/Provide:
  - Technology Impact Matrix (TIM)
  - Compatibility Matrix
  - Computation Metamodels for Metric Response
  - Multi-Attribute Decision Making Strategy
- GA yields:
  - best combination of technologies based on identified measures and provided information



# Genetic Algorithm Function Calls





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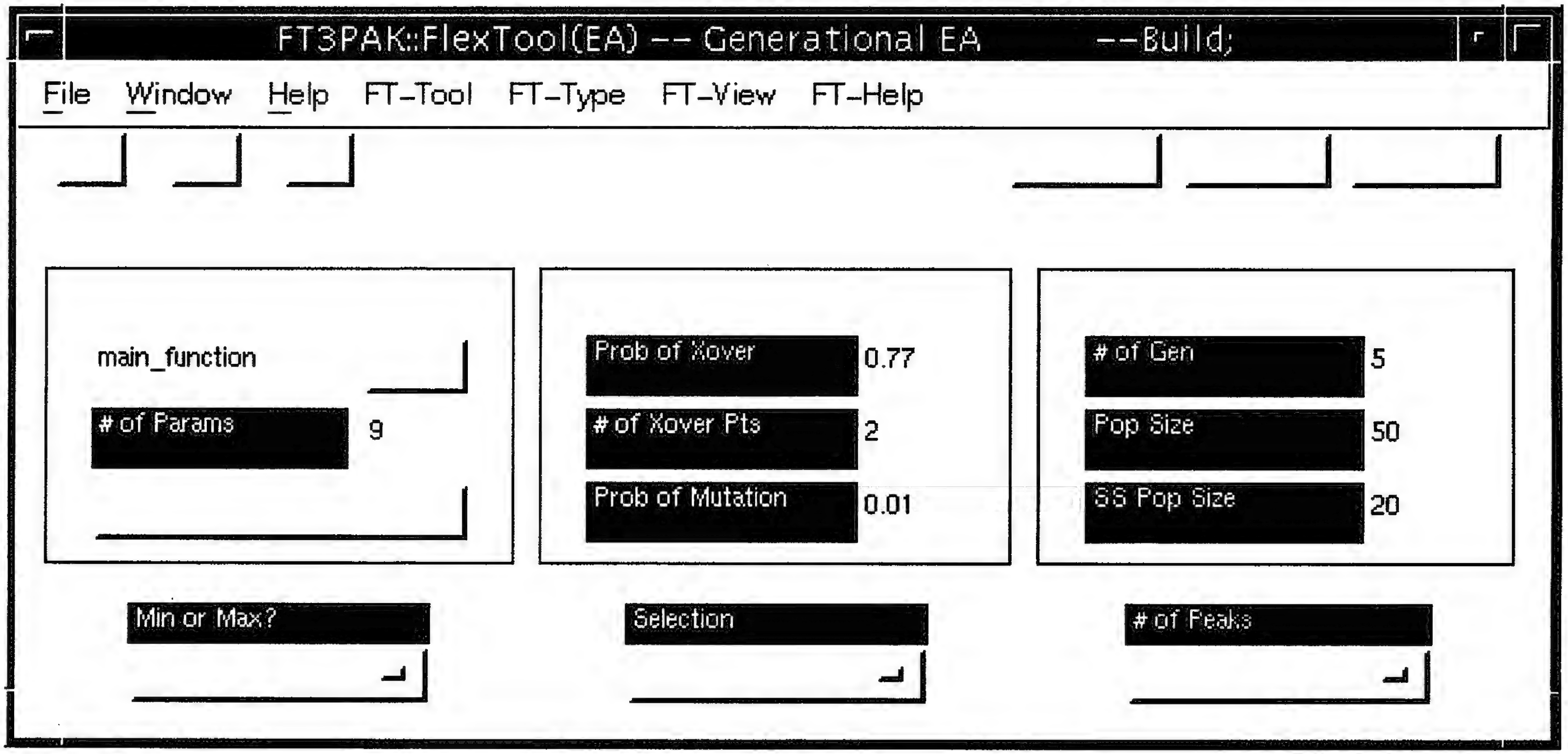
# Specification of GA parameters



# Conclusions

- A methodology for the systematic down-select of the proper mix of technologies which satisfies the imposed system level metrics was established
- Method could be interpreted for resource allocation of various technologies
- Future work will focus on:
  - probabilistic and stochastic evaluation
  - multi-attribute decision making with conflicting objectives
  - more technology combinations for GA implementation
  - other vehicle concepts

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# Multi Criteria Decision Making Technique for Systems Design: Joint Probabilistic Decision Making (JPDM)

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# Hypothesis: Multi Criteria Motivation

- Customer needs translate to system characteristics called attributes or constraints which become decision criteria for product selection.
- Complex systems have a multitude of attributes, such as life cycle cost, gross weight, excess power, safety, dependability, etc.
- Decisions based on one criterion/attribute may yield products with poor performance in other attributes.

A design method is needed that accounts for all criteria concurrently.

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# Hypothesis: Probabilistic Motivation

- Most assumptions made about the operational environment of the system are uncertain.

➡ Deterministic assumptions misrepresent the actual behavior/knowledge.

- Computer model fidelity introduces uncertainty in the output prediction.

- Use of new technologies adds uncertainty due to readiness/availability.

➡ A probabilistic formulation of the design process is needed to capture and analyze uncertainties.

# Typical Design Questions

- How to compare different design solutions with multiple objectives on an equal basis.
- How to compare different design solutions despite uncertainty about relevance and accuracy of design assumptions.
- How to trade one requirement for another.
- How to determine optimal solutions based on multiple objectives.

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# Shortcomings of Existing Decision Aids

Current multi criteria approaches determine either just the best solution of a small finite set based on many criteria, called Multi Attribute Decision Making (MADM), or the best solution of an infinite set based on just a few criteria, called Multi Objective Decision Making (MODM).

| | | Alternatives | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | ..... | Alt N |
| Criteria | Crit 1 | Value | Value | Value | Value | Value | | Value |
| | Crit 2 | Value | Value | Value | Value | Value | | Value |
| | Crit 3 | Value | Value | Value | Value | Value | | Value |
| | Crit 4 | Value | Value | Value | Value | Value | | Value |
| | Crit 5 | Value | Value | Value | Value | Value | | Value |
| | ..... | | | | | | | |
| | Crit M | Value | Value | Value | Value | Value | | Value |

MODM

MADM

JPDM

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# Proposed Method

## Joint Probabilistic Decision Making (JPDM)

- Combines advantages of probabilistic treatment of uncertain information with multi criteria decision making.
- Determines the probability of satisfying all (specified) customer needs/criteria values as an objective function within TIES.
- Facilitates visual trade-offs for two requirements at a time.

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# Four Steps for Implementing JPDM

**Step 1:** Determine objectives/requirements of customer and designer.

**Step 2:** Assign probability distributions to design assumptions (fix design/control variables).

**Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.

**Step 4:** Determine solution with highest joint probability (two problems: MADM or MODM).

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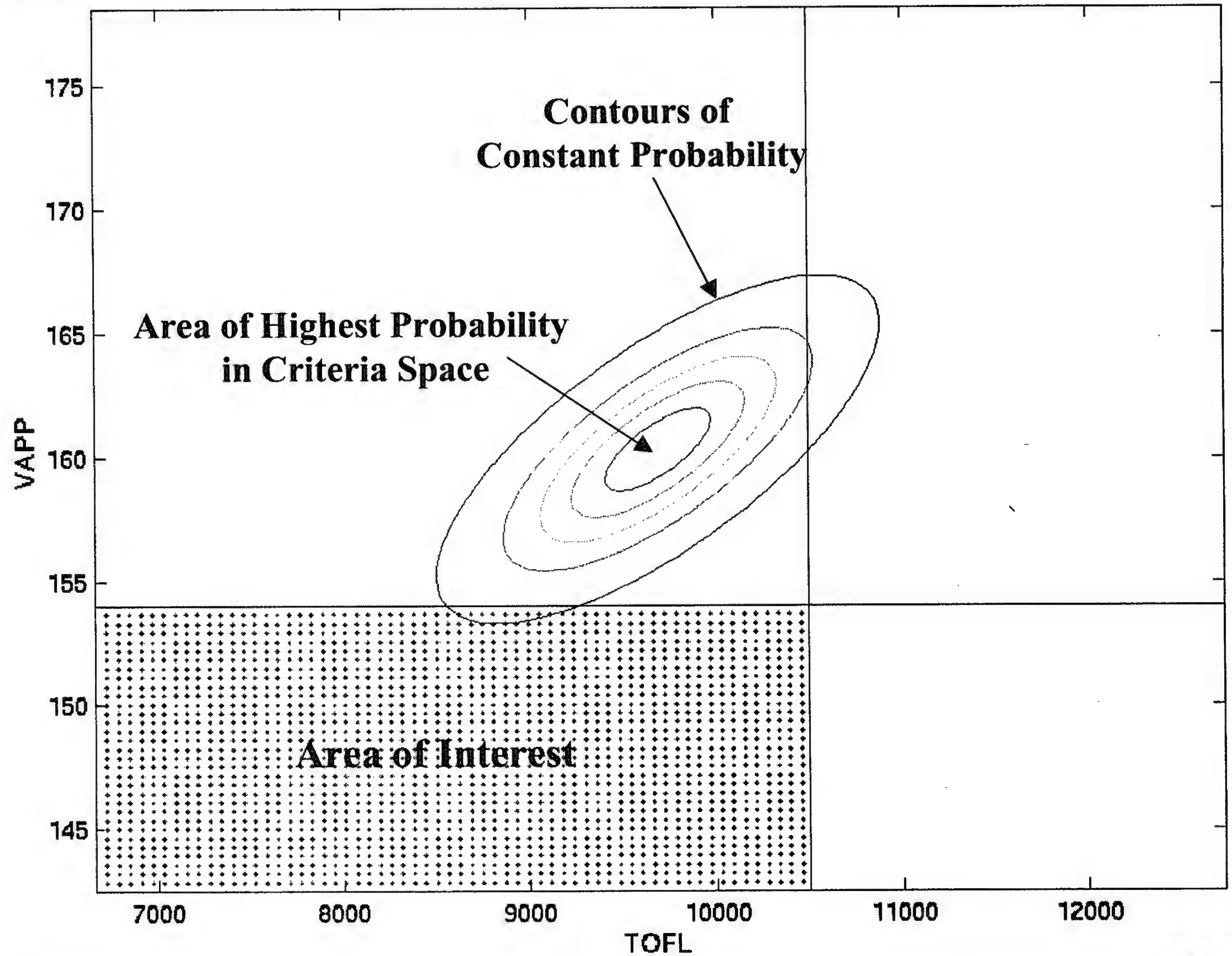
# Joint Probability Density Function - 2D

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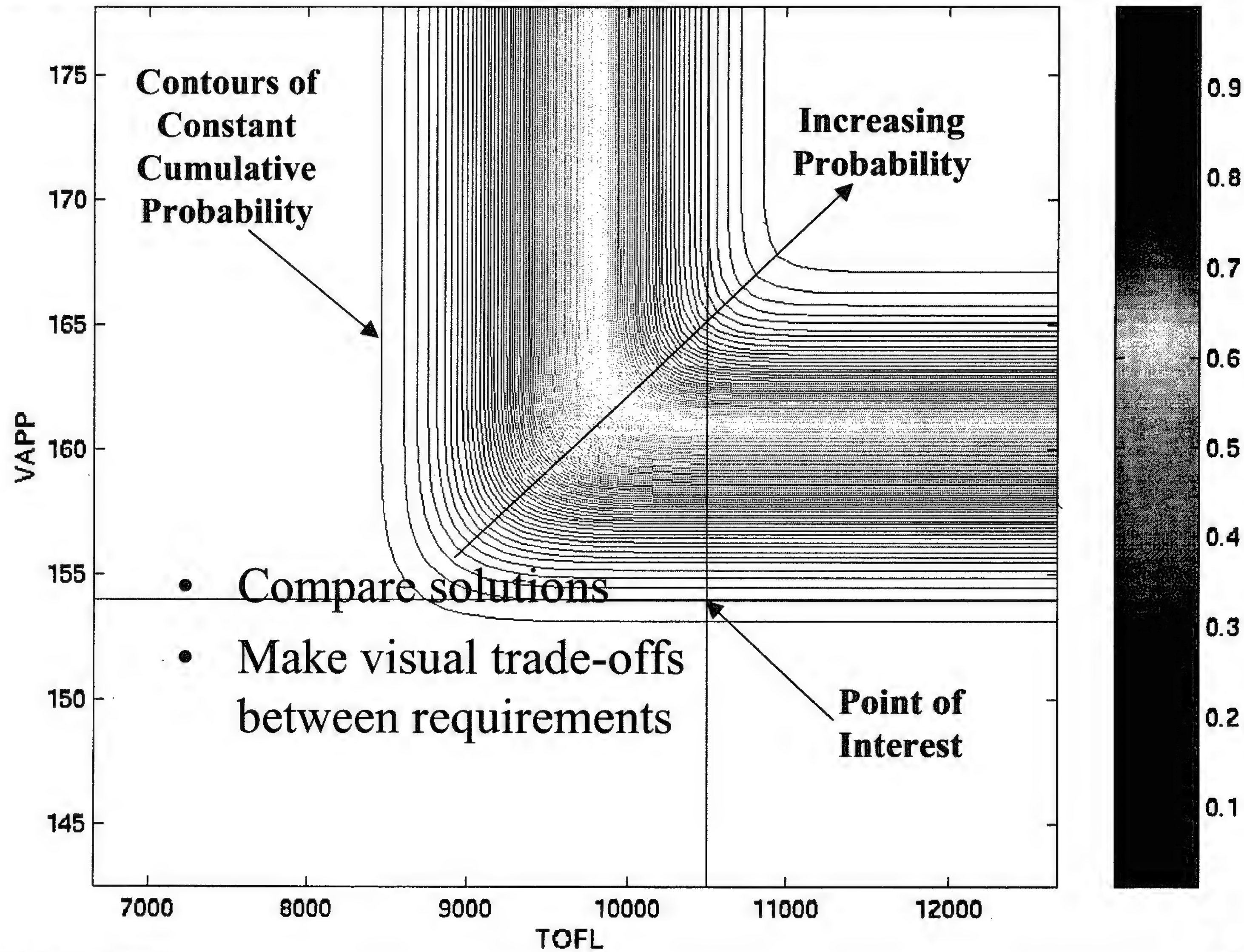
# Joint Cumulative Distribution Function - 2D




- Compare solutions
- Make visual trade-offs between requirements

# Implementation (cont'd)

**Step 1:** Determine objectives/requirements of customer and designer.

**Step 2:** Assign probability distributions to design assumptions (fix design/control variables).

**Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.

**Step 4:** Determine solution with highest joint probability (two problems: MADM or MODM).

# Empirical Distribution Function (EDF)

- Estimates probability of occurrence of a specified event based on sample events.
- Counts how many times the event occurred in the sample.
- Denoted for one variable and sample $x_i$, i=1 to n by

Density function: $$f_X(a) = \frac{1}{n}\sum_{i=1}^{n} I(x_i = a) \qquad I(x_i = a) = \begin{cases} 1 \text{ if true} \\ 0 \text{ if false} \end{cases}$$

Cumulative function: $$F_X(a) = \frac{1}{n}\sum_{i=1}^{n} I(x_i \le a) \qquad I(x_i \le a) = \begin{cases} 1 \text{ if true} \\ 0 \text{ if false} \end{cases}$$

- Joint cumulative formulation, sample $(x_i, y_i, z_i)$, i=1 to n:

$$F_{XYZ}(a,b,c) = \frac{1}{n}\sum_{i=1}^{n} I(x_i \le a, y_i \le b, z_i \le c)$$

# EDF - Advantages/Disadvantages

- Advantages:
  - Most exact method
  - Does not need approximation with standard distributions
  - Estimates joint probability from data directly

- Disadvantages:
  - Needs large amount of data to be accurate
  - Requires modeling and simulation
  - Availability of data in conceptual and preliminary design may be limited or too expensive
  - Joint probability estimation itself is more time consuming

# Joint Probability Model (JPM)

- Analytical model to estimate multivariate joint probability.
- Uses statistics of marginal distributions (mean $\mu$ and standard deviation $\sigma$).
- Uses correlation coefficients of criteria.
- Allows continued use of techniques that estimate marginal distributions.
- Example for bivariate normal model:

$$f_{XY}(a,b) = \frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2}} \exp\{\frac{1}{2\rho^2-2}[(\frac{a-\mu_X}{\sigma_X})^2 - 2\rho(\frac{a-\mu_X}{\sigma_X})(\frac{b-\mu_Y}{\sigma_Y}) + (\frac{b-\mu_Y}{\sigma_Y})^2]\}$$

- Formulation for n-variate normal model:

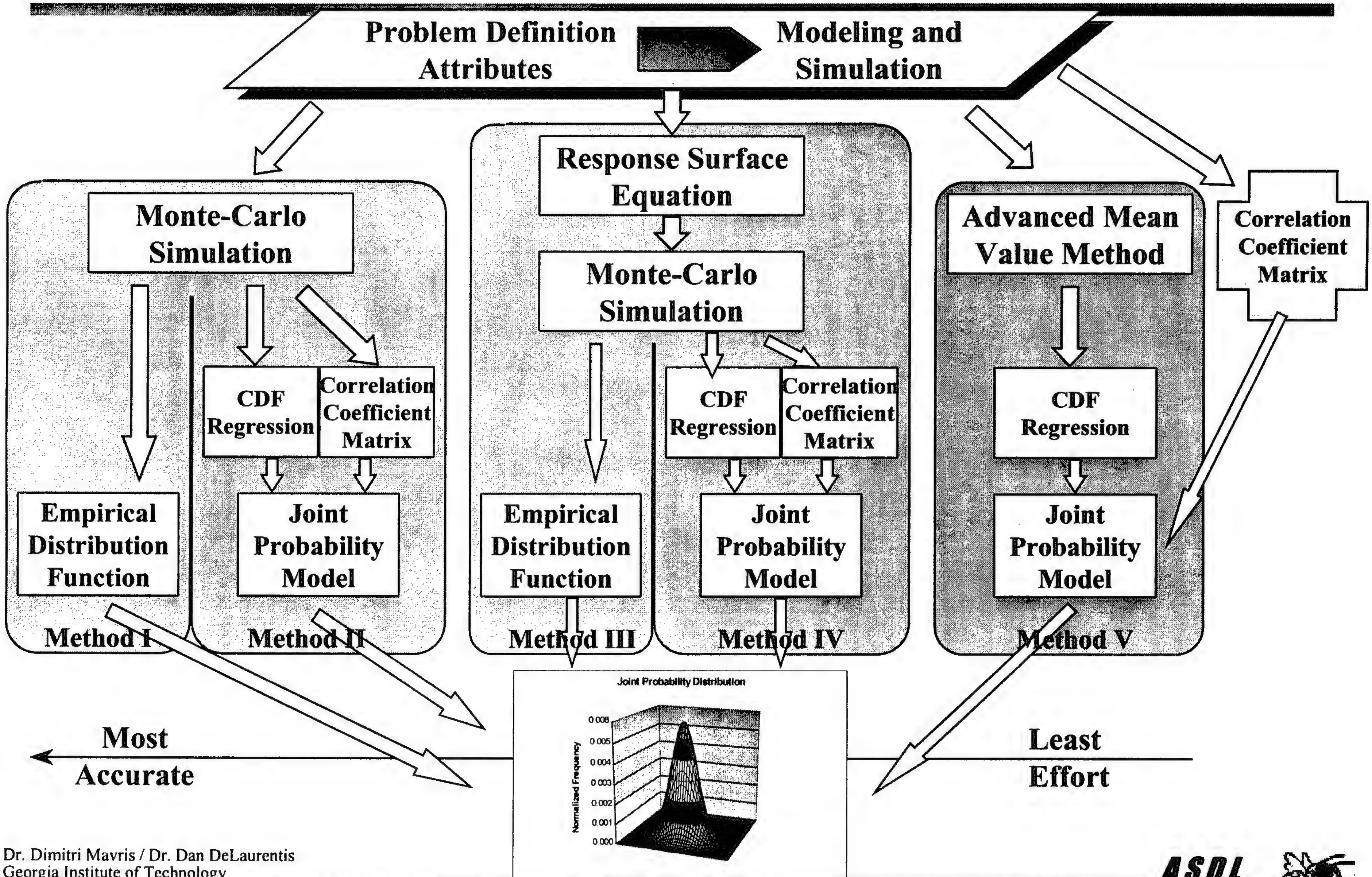
$$f(\mathbf{x};\boldsymbol{\mu},\boldsymbol{\Sigma}) = \frac{1}{(2\pi)^{n/2}|\boldsymbol{\Sigma}|^{1/2}} e^{-Q_n(\mathbf{x};\boldsymbol{\mu},\boldsymbol{\Sigma})/2}, \quad Q_n(\mathbf{x};\boldsymbol{\mu},\boldsymbol{\Sigma}) = (\mathbf{x}-\boldsymbol{\mu})'\boldsymbol{\Sigma}^{-1}(\mathbf{x}-\boldsymbol{\mu}),$$

$$\mathbf{x} \in \Re^n \qquad \Sigma = \text{Correlation Coefficient Matrix}$$

# JPM - Advantages/Disadvantages

- Advantages:
  - Needs limited information for execution
  - Can employ expert guesses in case of lack of simulation
  - Fast evaluation of joint probability
  - Method can be used in conceptual or preliminary design
- Disadvantages:
  - Requires approximation of actual data by standard distribution
  - Requires correlation coefficient, which may not be available in early stages of design

# Step 3 - Exeuction Accuracy Vs. Efficiency

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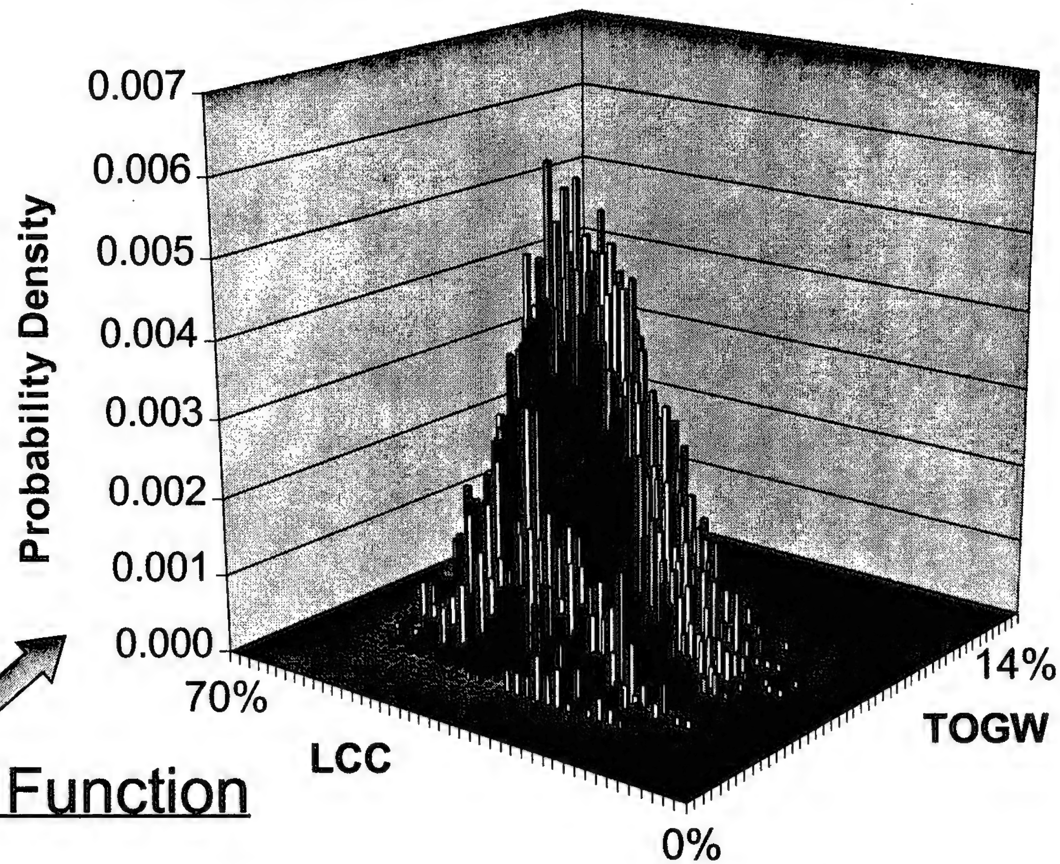
# Results - Method I

## Monte Carlo Simulation

10,000 samples

| LCC | TOGW |
|---|---|
| 10.5% | 2.3% |
| 5.3% | 1.2% |
| 43.8% | 12.5% |
| • | • |
| • | • |
| • | • |

**Joint Probability Distribution**




## Empirical Distribution Function

$$f(LCC,TOGW)=\frac{1}{10,000}\sum_{i=1}^{10,000} I(LCC-\varepsilon < lcc_i \leq LCC+\varepsilon, TOGW-\varepsilon < togw_i \leq TOGW+\varepsilon)$$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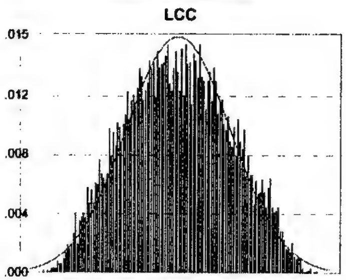
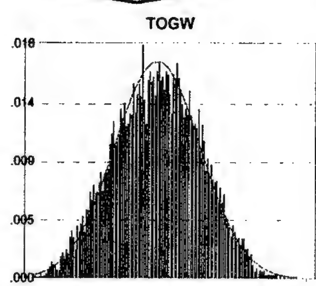
# Results - Method II

## Monte Carlo Simulation

10,000 samples

| LCC | TOGW |
| --- | --- |
| 10.5% | 2.3% |
| 5.3% | 1.2% |
| 43.8% | 12.5% |



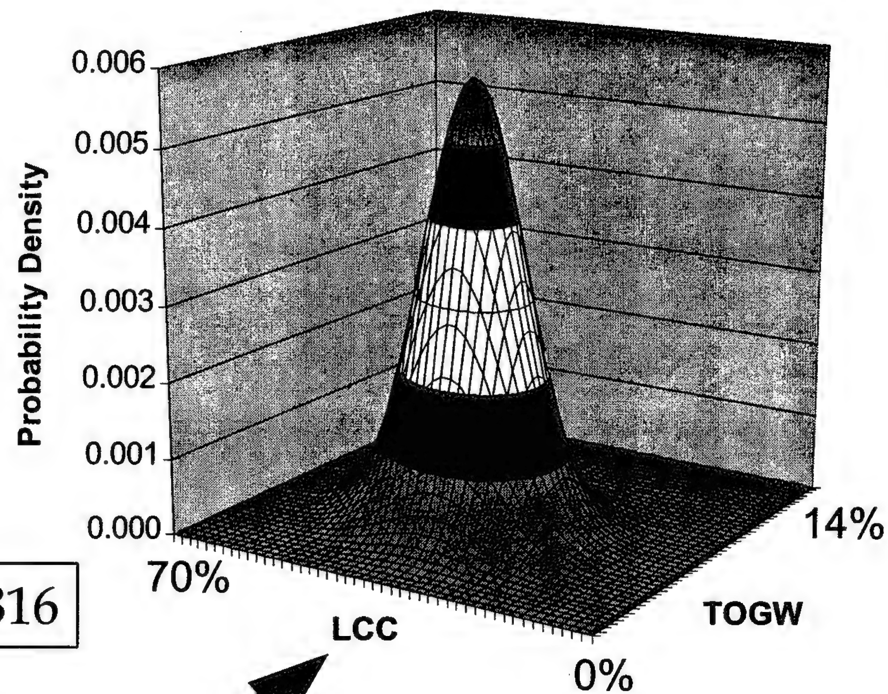




LCC: μ=29.23%, σ=7.69%

TOGW: μ=6.70%, σ=1.77%

$\rho = -0.1816$

Joint Probability Distribution




$$f_{XY}(a,b) = \frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2}}\exp\{\frac{1}{2\rho^2-2}[(\frac{a-\mu_X}{\sigma_X})^2 - 2\rho(\frac{a-\mu_X}{\sigma_X})(\frac{b-\mu_Y}{\sigma_Y}) + (\frac{b-\mu_Y}{\sigma_Y})^2]\}$$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# Results - Method III

## DOE (147 cases)

| | LCC | TOGW |
|---|---|---|
| -1 -1 -1 -1 -1 -1 -1 -1 -1 | 10.5% | 5.1% |
| -1 1 -1 1 -1 1 -1 1 -1 | 25.7% | 7.9% |
| 1 -1 -1 1 1 -1 -1 -1 1 | 4.8% | 1.2% |
| • | • | • |

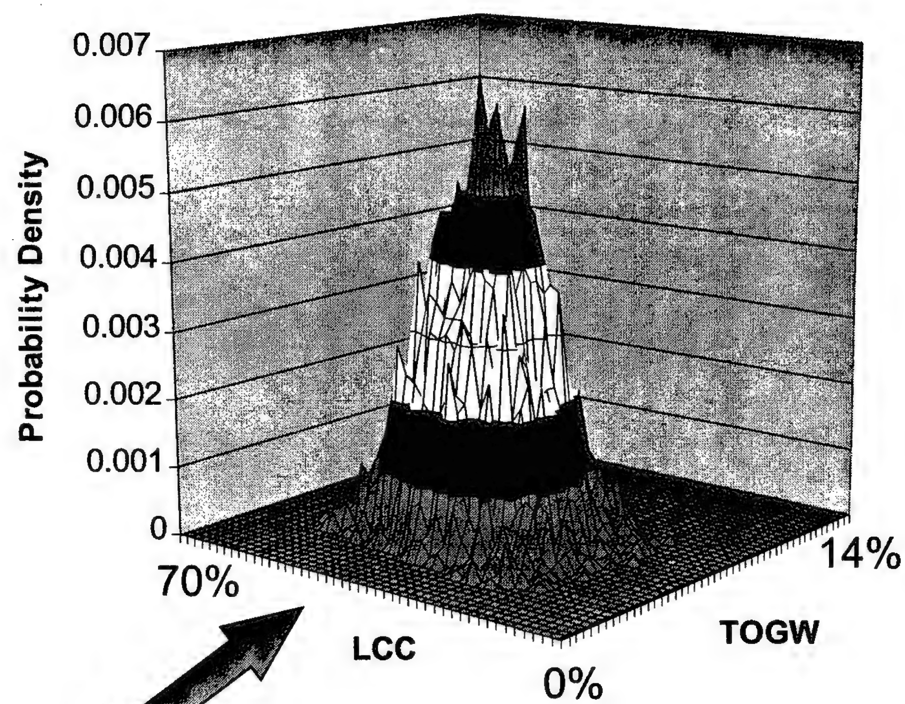
## Response Surface Equation

## Monte Carlo Simulation

10,000 samples from RSE

## Empirical Distribution Function

Joint Probability Distribution




$$f(LCC,TOGW)=\frac{1}{10{,}000}\sum_{i=1}^{10{,}000} I(LCC-\varepsilon<lcc_i\le LCC+\varepsilon, TOGW-\varepsilon<togw_i\le TOGW+\varepsilon)$$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# Results - Method IV

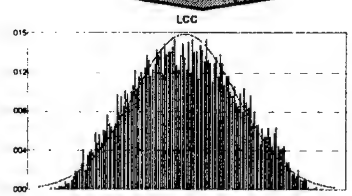
## DOE (147 cases)

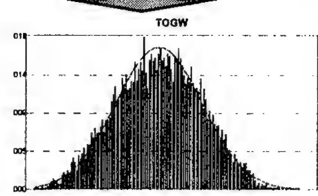
| | | | | | | | | | LCC | TOGW |
|---|---|---|---|---|---|---|---|---|---|---|
| -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | 10.5% | 5.1% |
| -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 25.7% | 7.9% |
| 1 | -1 | -1 | 1 | 1 | -1 | -1 | -1 | 1 | 4.8% | 1.2% |
| • | | | | | | | | | • | • |

Response Surface Equation

Monte Carlo Simulation

10,000 samples from RSE

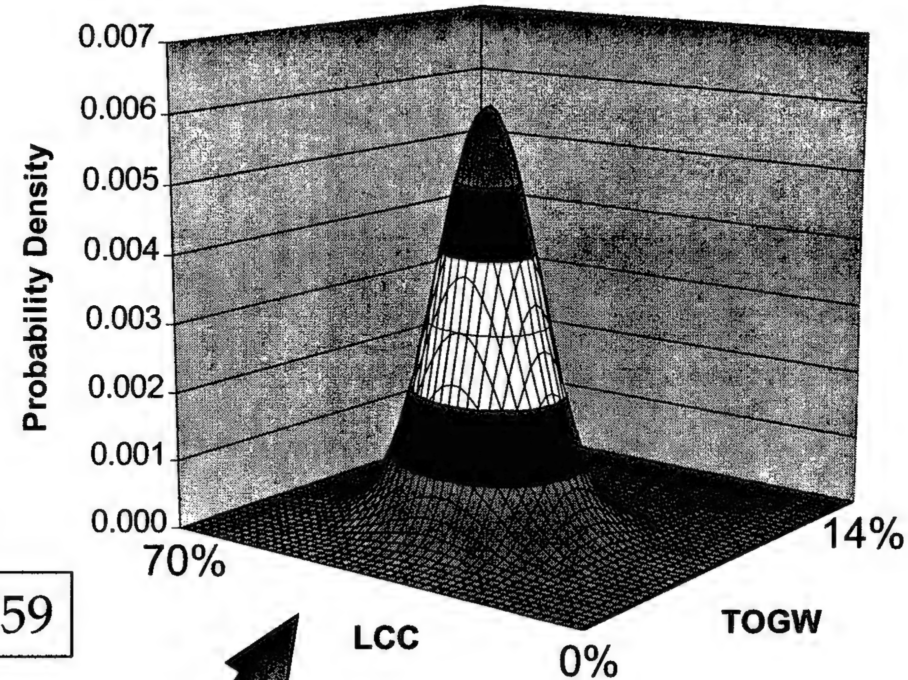



$\mu$=28.71%
$\sigma$=7.32%

$\mu$=6.66%
$\sigma$=1.76%

$\boxed{\rho=-0.159}$




$$f_{XY}(a,b)=\frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2}}\exp\{\frac{1}{2\rho^2-2}[(\frac{a-\mu_X}{\sigma_X})^2-2\rho(\frac{a-\mu_X}{\sigma_X})(\frac{b-\mu_Y}{\sigma_Y})+(\frac{b-\mu_Y}{\sigma_Y})^2]\}$$

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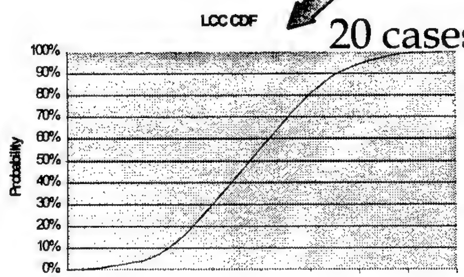
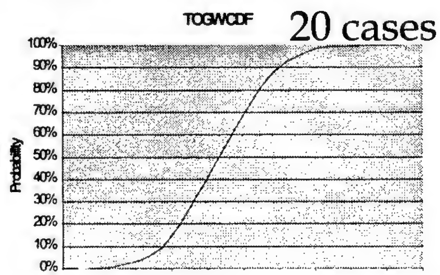
# Results - Method V

AMV

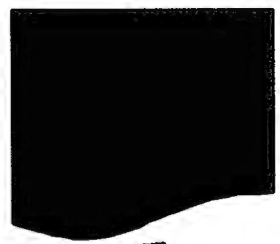


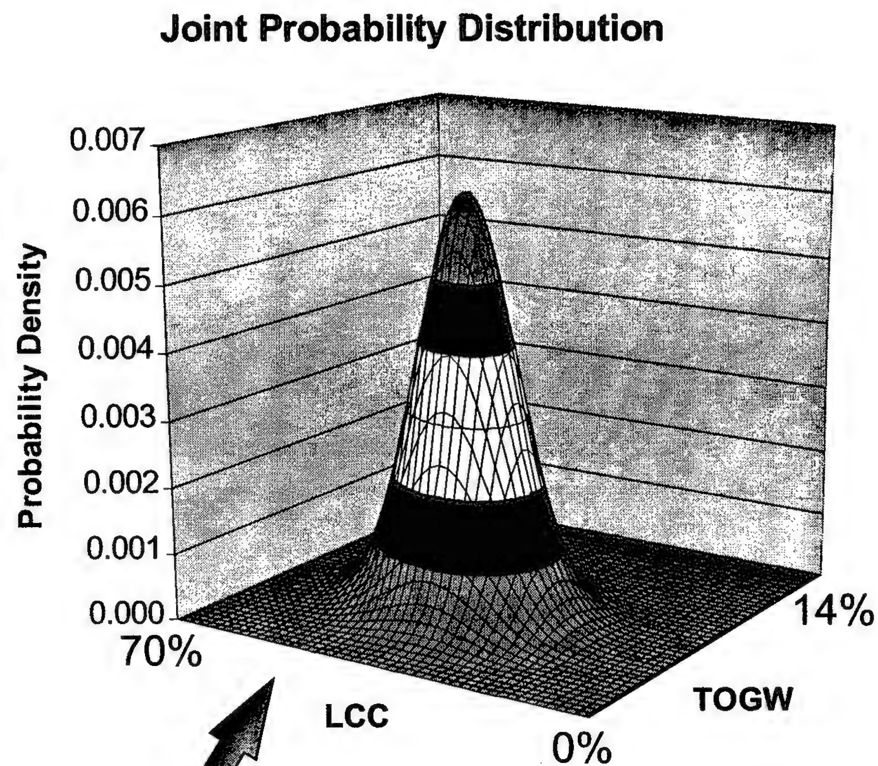

$\mu$=28.46%

$\sigma$=7.27%



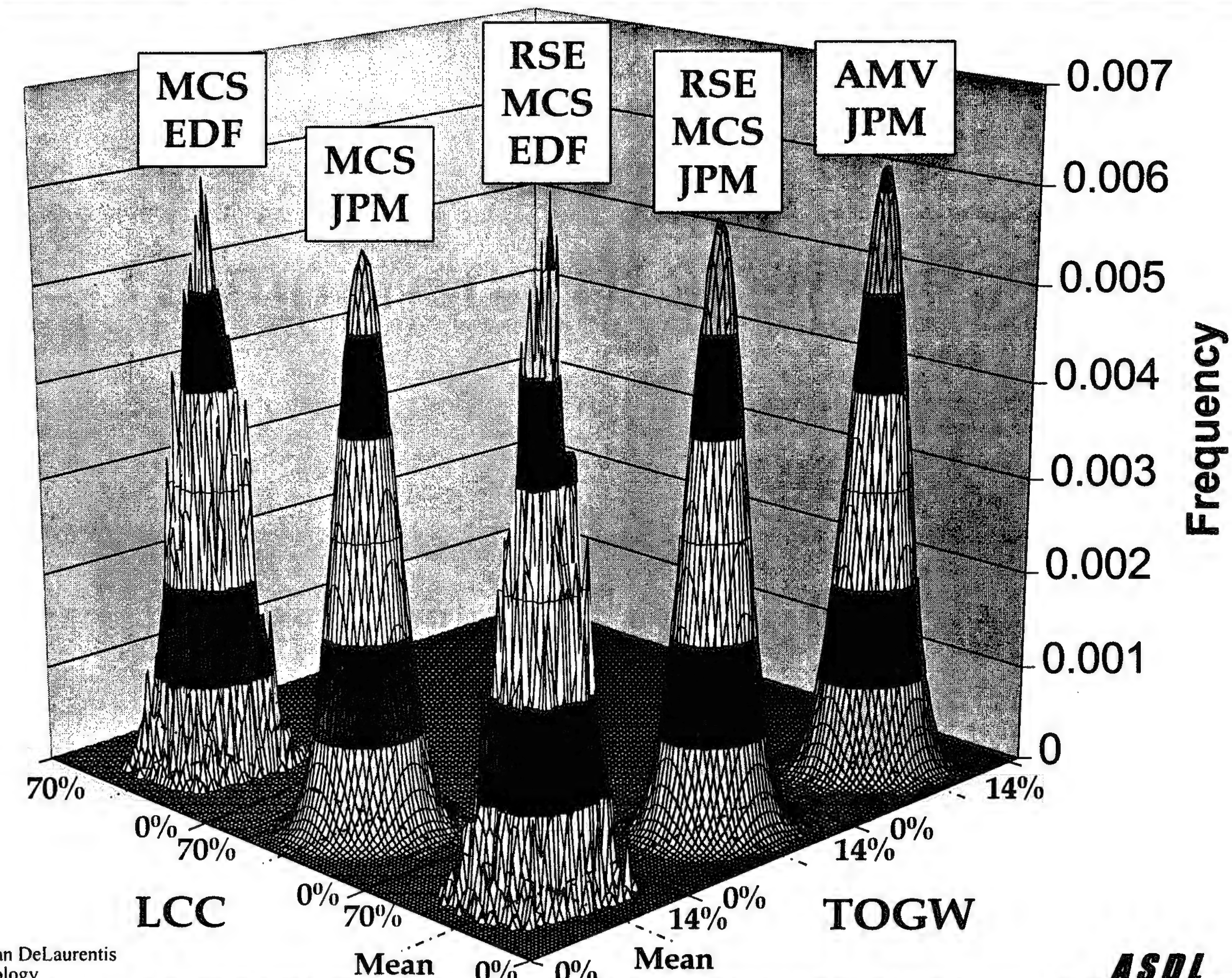

$\mu$=6.61% $\sigma$=1.73%






$$f_{XY}(a,b)=\frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2}}\exp\{\frac{1}{2\rho^2-2}[(\frac{a-\mu_X}{\sigma_X})^2-2\rho(\frac{a-\mu_X}{\sigma_X})(\frac{b-\mu_Y}{\sigma_Y})+(\frac{b-\mu_Y}{\sigma_Y})^2]\}$$

# Comparison of all JPDFs

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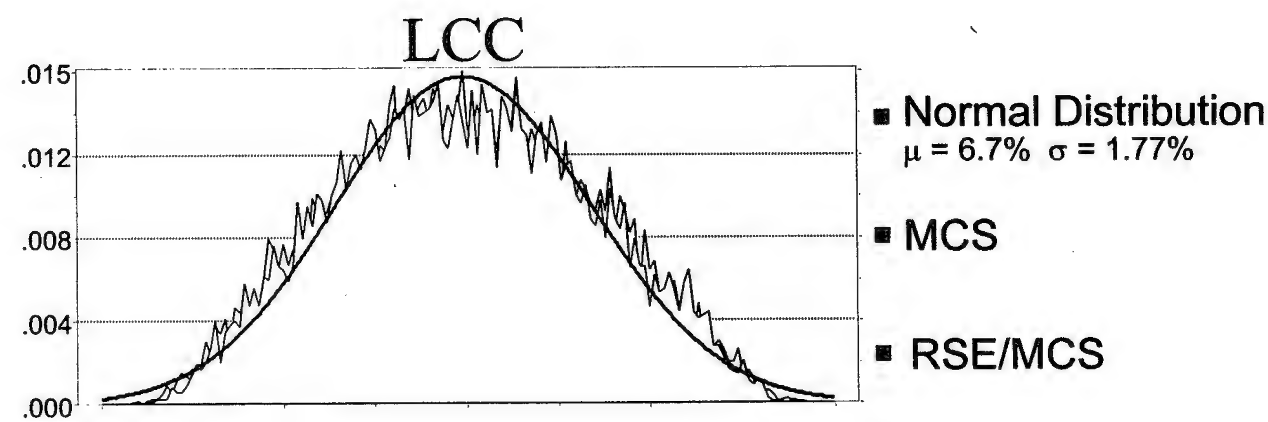
# Comparison of Methods

- Good agreement of Response Surface Equation/Monte Carlo Simulation method and Monte Carlo Simulation directly on analysis code.
- Both distributions are approximated well by the normal distribution (due to nine input variables and the Central Limit Theorem).
- Normal approximation will be even better for non-uniform input distributions.

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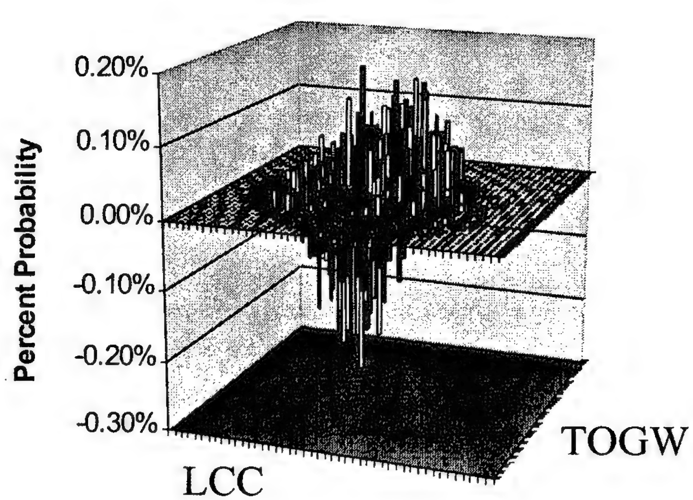
# Comparison of Methods (contd.)

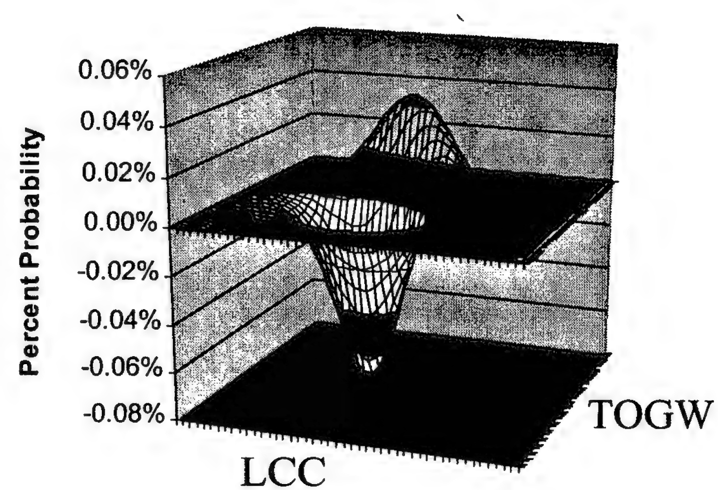
- Comparison of means and standard deviations shows similar prediction capability of methods.

| | MCS/JPM | RSE/JPM | % Difference | AMV/JPM | % Differenc |
|---|---|---|---|---|---|
| $\mu$LCC | 29.23% | 28.71% | -0.40% | 28.46% | -0.60% |
| $\mu$TOGW | 6.70% | 6.66% | -0.04% | 6.61% | -0.09% |
| $\sigma$LCC | 7.69% | 7.32% | -4.73% | 7.27% | -5.43% |
| $\sigma$TOGW | 1.77% | 1.76% | -0.60% | 1.73% | -2.53% |
| Correlation | -0.1816 | -0.1590 | -12.44% | (-0.1816) | - |

MCS/EDF - AMV/JPM




MCS/JPM - AMV/JPM

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# Implementation (cont'd)

**Step 1:** Determine objectives/requirements of customer and designer.

**Step 2:** Assign probability distributions to design assumptions (fix design/control variables).

**Step 3:** Run analysis and determine joint probability distribution of criteria and requirements.

**Step 4:** Determine solution with highest joint [illegible] problems: MADM or MODM).

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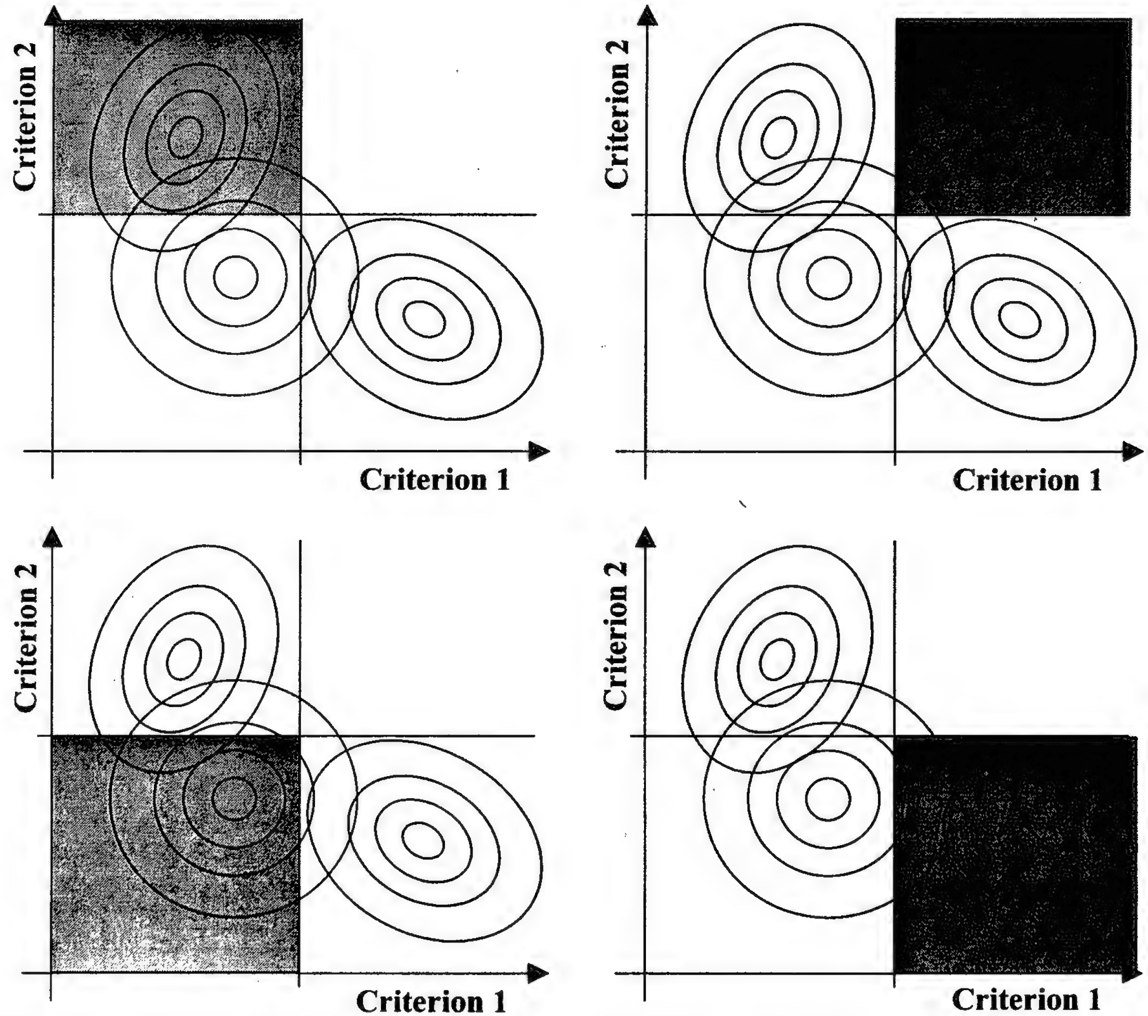
# Step 4 - MADM

- Rank solutions based on joint probability.
- Select solution with highest probability.
- Conduct "What-If" studies for requirements/ criteria.

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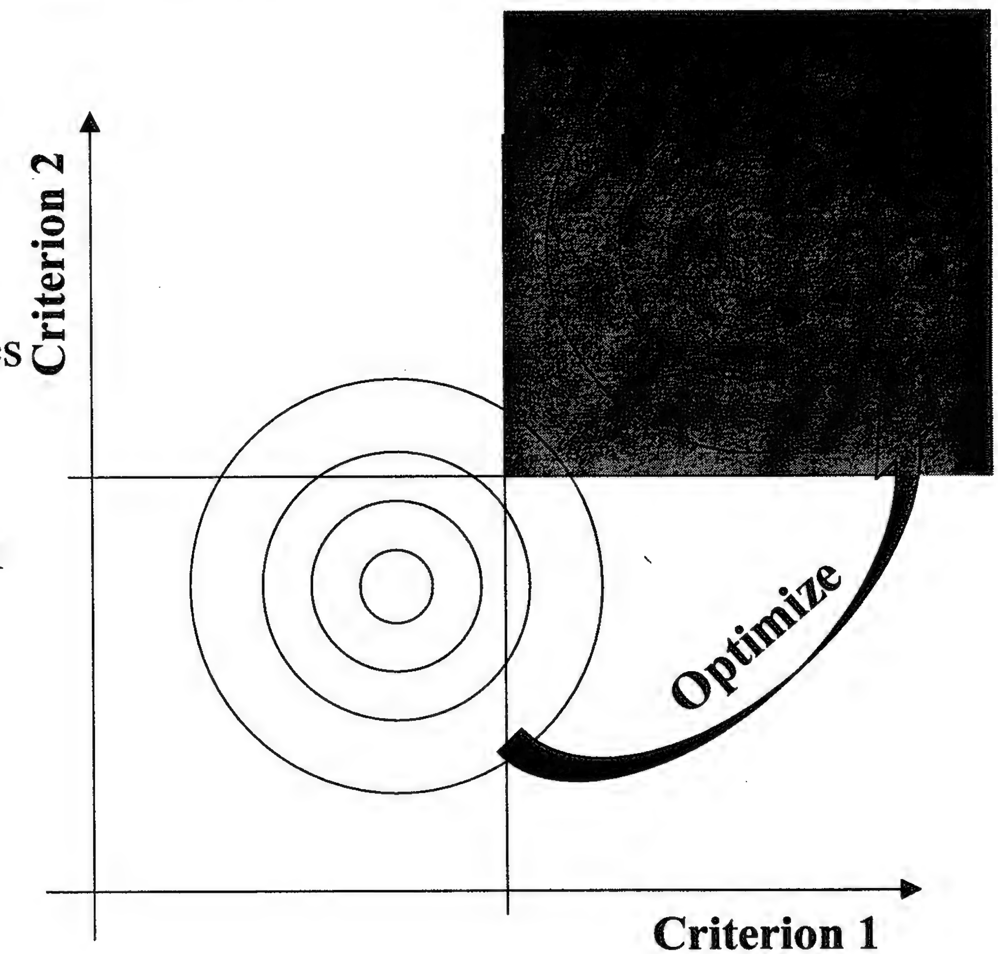
# Step 4 - MODM

- Use joint probability as an objective function for generic optimizer.
- Use design/control variables as independent variables.
- Determine optimal solution with maximum probability of satisfying all requirements/criteria.

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# Conclusions

- A four step joint probabilistic decision making technique was introduced as part of the TIES method.
- Five JPDM methods (MCS/EDF, MCS/JPM, RSE/MCS/EDF, RSE/MCS/JPM, and AMV/JPM) were used to determine the joint probability example study with two criteria.
- JPDM technique is capable of treating uncertain information of early stages in design.
- JPDM technique introduces new objective function to multi criteria decision making: *probability of meeting all operational and design requirements concurrently*.
- JPM needs extension to capture other than normal distributions.

# Section 4

1. ***Introduction and Research Setting/Summary***

2. ***Overall Technical Approach for Affordable Systems Design***

3. ***Methods Implementation and Testbed Applications***

4. ***Key Advancements in Method Components***

5. ***Conclusions/Summary***

# Section 4

# Part A: Simultaneous Examination of Requirements and Technologies

# Examining the Role of *Requirements*

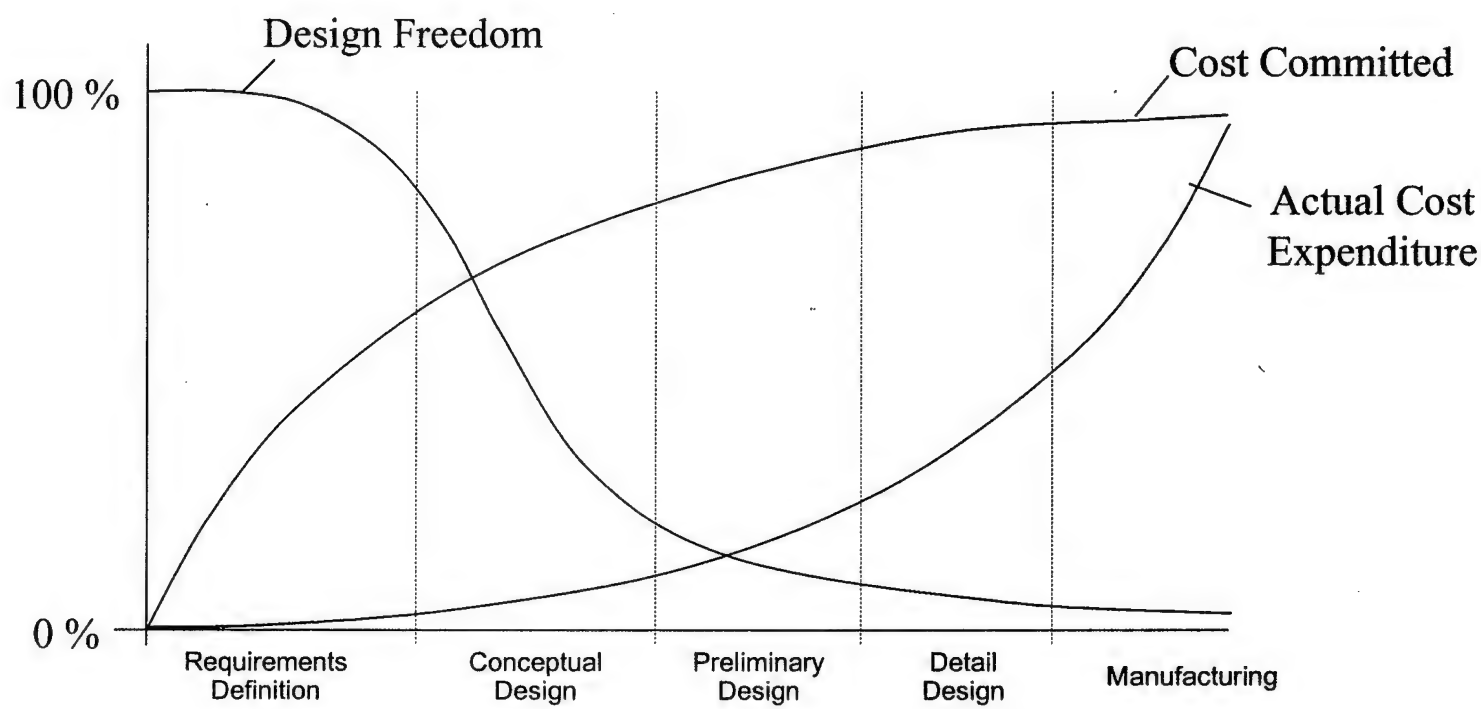
## Synopsis

- Requirements drive initial design studies, procurement decisions, and ultimately *operational effectiveness and cost*
- However, it is often the case that design processes (and designers) overlook the impact of changes and/or ambiguity in requirements and fail to understand the relationships between requirements, technologies, and the design space
- ASDL has been tasked by ONR to investigate the role of requirements in affecting the design and S&T investment; and then to formulate a method for examining requirements simultaneously with design alternatives, technologies, affordability, etc.

## Tasks

- Link the appropriate aircraft sizing/synthesis and economic tools plus probabilistic methods to create testbed environment; model the F/A-18C (using substantiation data for validation)
- With F/A-18E/F requirements (Ref. AIAA Paper 98-4701) as drivers, look at relation of technology metrics on requirements mathematically
- Provide ONR with the unique capability to examine the impact of requirements, desirements, and constraints on affordability decisions

# The Importance of the Requirements Definition Stage

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# Expanding Missions: The F/A-18E/F

<table>
<tr><th>Maritime Air Superiority</th><th>Air Combat Fighter</th><th>Fighter Escort</th><th>Recce</th><th>Close Air Support</th><th>Air Defense Suppres-sion</th><th>Day/ Night Attack</th><th>All Weather Attack</th></tr>
<tr><td>F-14D<br>NATF</td><td colspan="5">F/A-18<br>A/B/C/D</td><td colspan="2">A-6F</td></tr>
<tr><td colspan="8">F/A-18 E/F</td></tr>
</table>

*Ref. Young, et.al. AIAA-98-4701, 1998.*

How can such multi-role vehicles be examined as potential solutions for the war-fighter with respect to technologies, requirements, and design constraints ?

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# Affordability: Components and Definitions

A design or S&T investment problem has the following top level structure:

**Affordability**

| **Requirements** | **Desirements** | **Constraints** |
|---|---|---|
| Requirements are thresholds on performance or cost metrics which must be satisfied ***(e.g. Mission Radius must be greater than 500 nm)*** | Desirements are metrics which are desired to be maximized (or minimized) to delineate between competing alternatives which satisfy the requirements ***(e.g. Minimize O&S fleet costs)*** | Constraints are externally imposed requirements (either by nature or government regulations, communities, market, etc.) ***(e.g. Keel must be of sufficient strength to handle carrier landing)*** |

This structure provides the starting point for the TIES F/A-18C process....

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# Process

The traditional process of identification of an overall objective to be optimized is replaced by the following process:

1) Using Response Surface Method to mathematically represent combined requirements-technology-configuration space

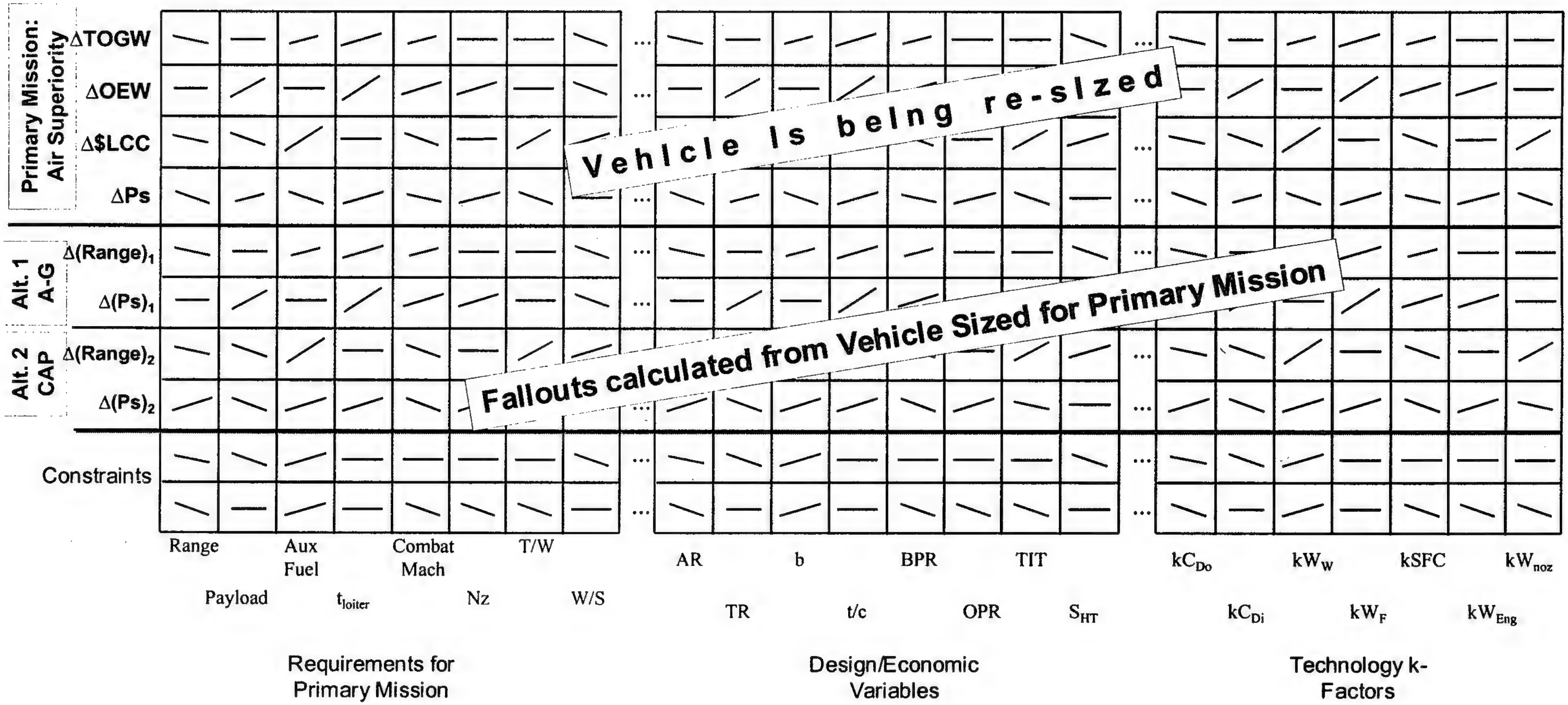
2) search for alternatives (configuration changes plus technology infusion) that satisfy *requirements and constraints (TIES method)*

3) simultaneously, optimize on desirements within this feasible space (continuous) or set (discrete) then, perform sensitivity studies to show the perturbation of the solution due to *possible* changes in requirements and design variables.

**Thus, the customer/decision maker has information with regards to the choice between tolerating a *relaxation in requirements* or *accepting achievable performance* levels**

# Overall Environment Snapshot

## Example: Examine a multi-role fighter/attack concept

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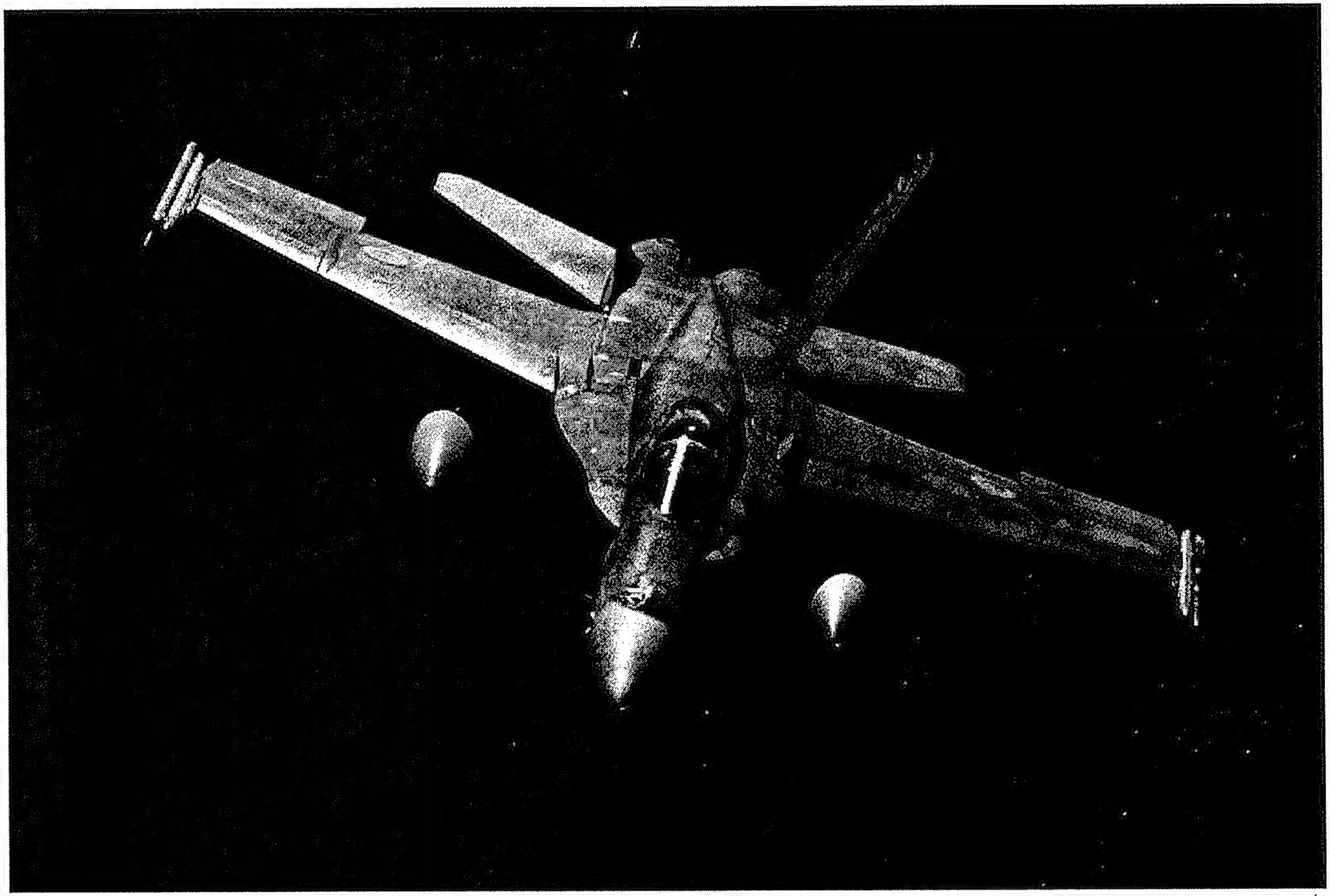
# F/A-18C Modeling



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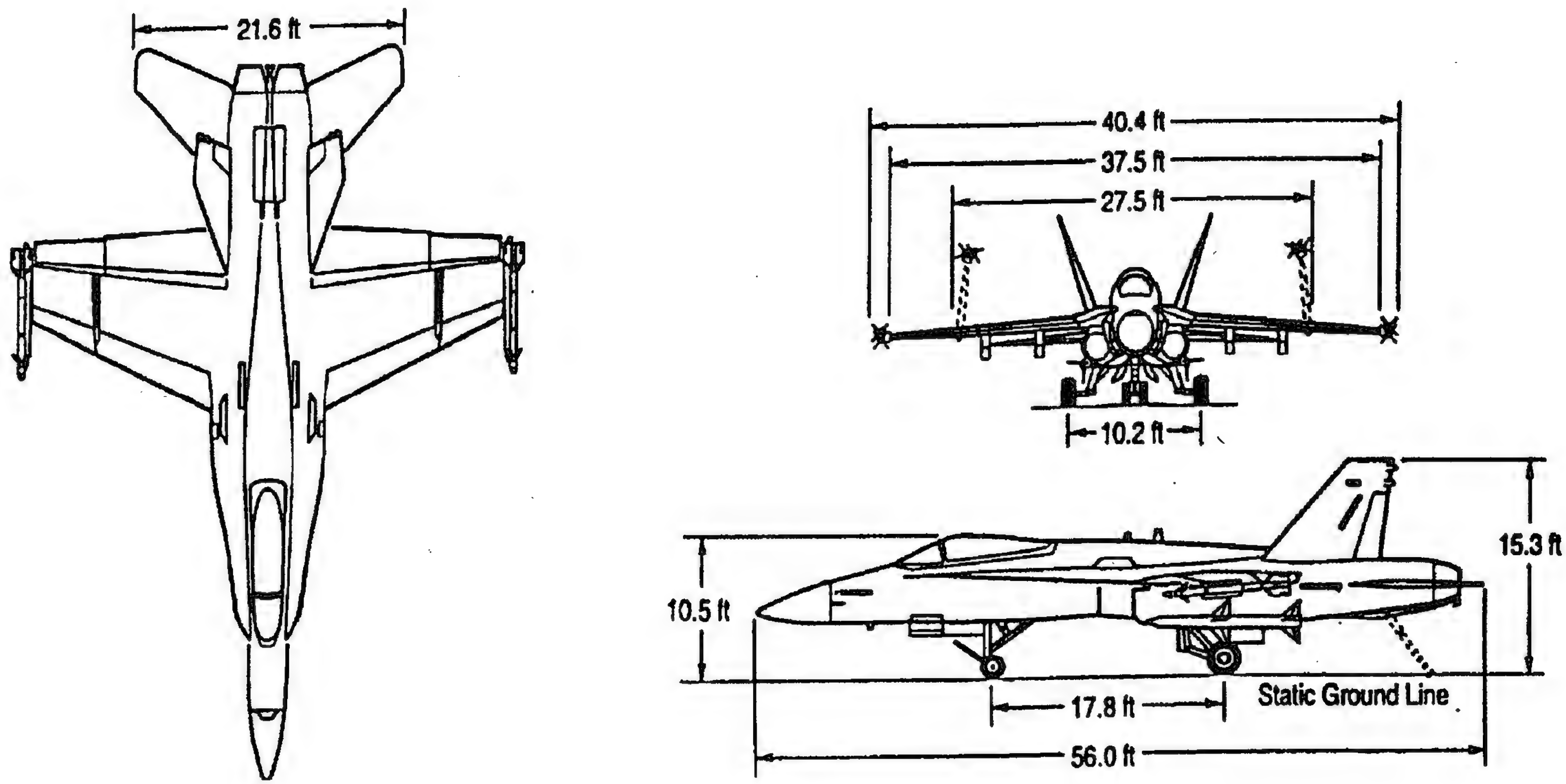
# Basic Geometry

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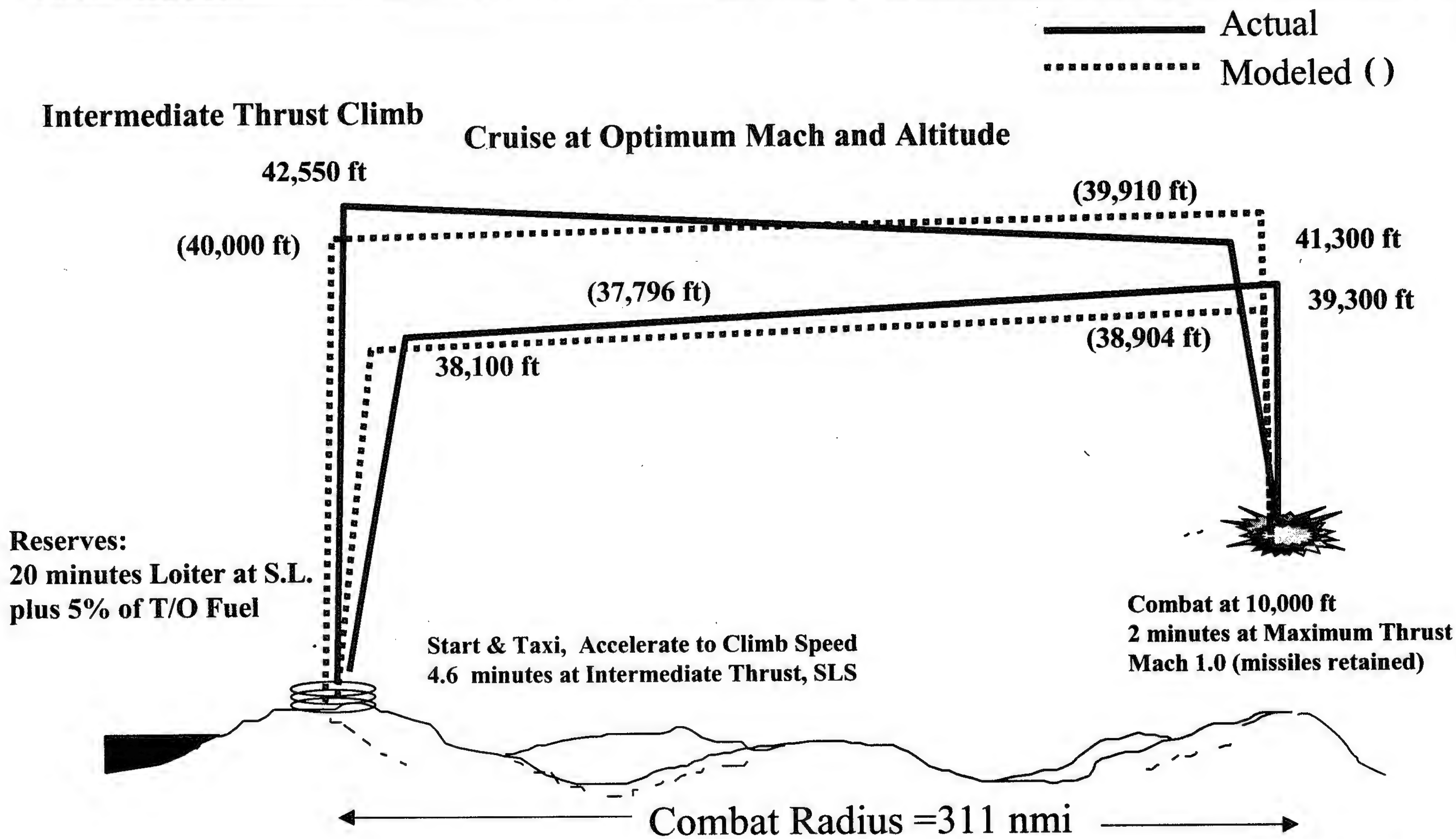
# Primary Mission- Fighter Escort

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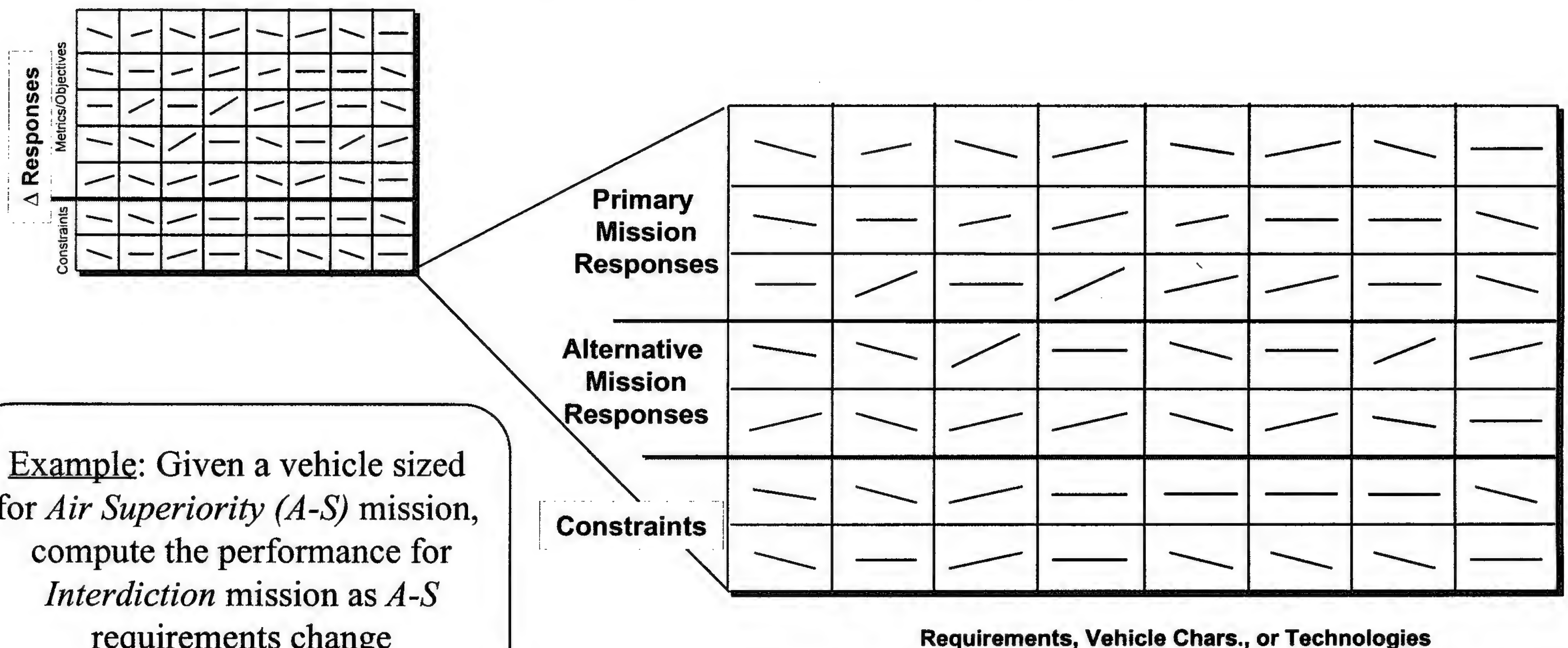
# Alternate Missions- Addressing Multi-role Capability

- Requirements can include performance against a wide variety of missions

- Vehicle sizing proceeds based on a primary mission and then fallout performance of the sized vehicle on alternate missions is computed and tracked




Example: Given a vehicle sized for *Air Superiority (A-S)* mission, compute the performance for *Interdiction* mission as *A-S* requirements change

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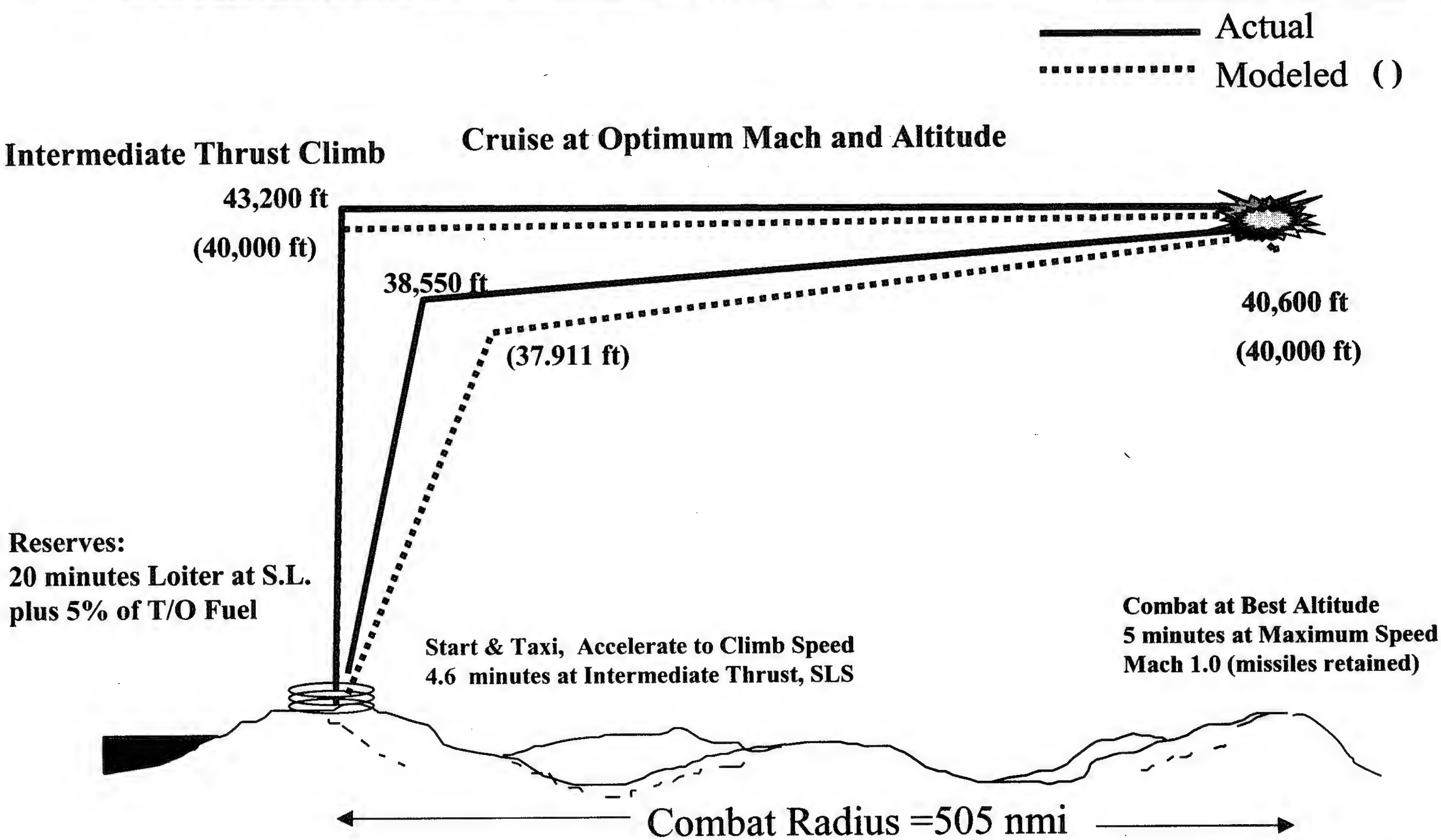
# Alternate Mission: Hi Hi Hi





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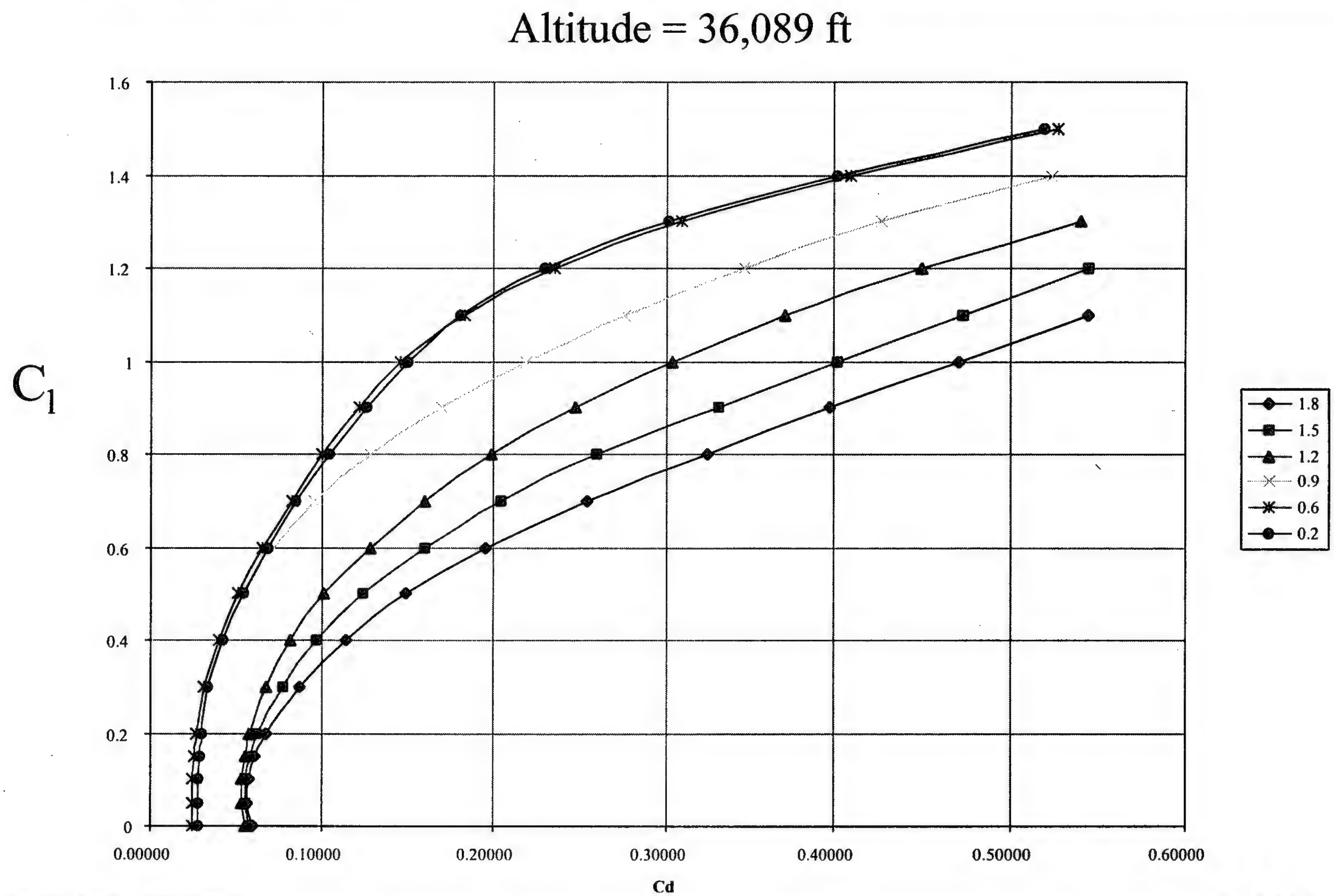
# Drag Polars for Varying Mach Numbers



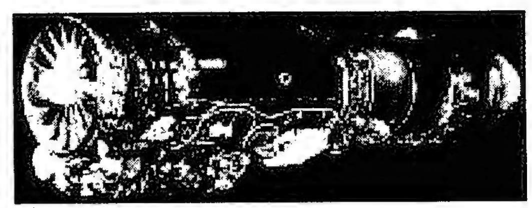
# Propulsion Modeling

### *F404-GE-402 Augmented Turbofan Engine*

- The F404-GE-402 is an increased performance derivative of the F404 and is used in the F/A-18C
- Features a dual-spool mixed flow turbofan architecture, 3X7X1X1 turbomachinery configuration
- F404 Engine performance deck based on installed engine data for the F/A-18C
- Engine performance data source: "*F/A-18C Substantiating Performance Data with F404-GE-402 Engines*" Report MDC91B0290

**General Specifications:**

- Thrust: 17,700 lb
- SFC (max A/B): 1.74 lbm/lbf-hr
- SFC (IRP): 0.81 lbm/lbf-hr
- Airflow (SLS): 146 pps
- Weight: 2,282 lb
- Length: 159 in
- Diameter: 35 in



# Weight Breakdown- Validation

- Sizing/Synthesis Code Used: FLight OPtimization System (FLOPS)
- F/A-18C Baseline Modeled in FLOPS calibrated against actual substantiation data from manufacturer
- Highly accurate model (errors in weights less than 1%)

**F/A18C Weight Breakdown Comparison**

| Group | F/A18C | Baseline Model |
|---|---|---|
| Wing | 3,919 | 3,918 |
| Tail Group | 1,005 | 1,006 |
| Body | 5,009 | 5,009 |
| Alighting Gear | 2,229 | 2,228 |
| Propulsion Group | | |
| Engines | 4,420 | 4,417 |
| Engine Section<br>Gear Box<br>Controls<br>Starting System | 921 | 922 |
| Fuel System | 1,078 | 1,078 |
| Flight Controls | 1,061 | 1,062 |
| Auxiliary Power Plant | 206 | 206 |
| Instruments | 84 | 84 |
| Hydraulics | 351 | 352 |
| Electrical | 592 | 592 |
| Avionics | 1,864 | 1,864 |
| Armament, Gun, Launchers, Ejectors | 948 | 948 |
| Furnishings, Load/Handling, Contingency | 631 | 631 |
| Air Conditioning | 641 | 642 |
| Crew | 180 | 180 |
| Unusable Fuel | 207 | 207 |
| Engine Fluids | 114 | 115 |
| Chaff, Ammunition | 252 | 252 |
| Miscellaneous | 58 | 58 |
| **Operating Weight Empty** | **25,770** | **25,771** |
| Missiles | | 1,410 |
| (2) AIM-7F | 1,020 | |
| (2) AIM-9L | 390 | |
| Mission Fuel | 10,860 | 10,857 |
| **Takeoff Gross Weight** | **38,040** | **38,038** |

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# Economic Assumptions

- MALCCA (Military Aircraft Life Cycle Cost Analysis) in-house code used to determine notional aircraft economics

- Baseline File created starting with defaults based on the military aircraft assumptions (primarily sourced from F-15 and F-16 data)

| | |
|---|---|
| Inflation Factor | 3.3% |
| Dollar Year | 1994 |
| Year of Program Initiation | 2000 |
| Final Year of Production | 2023 |
| # Operational Vehicles | 2530 units |
| System Economic Life | 20 years |

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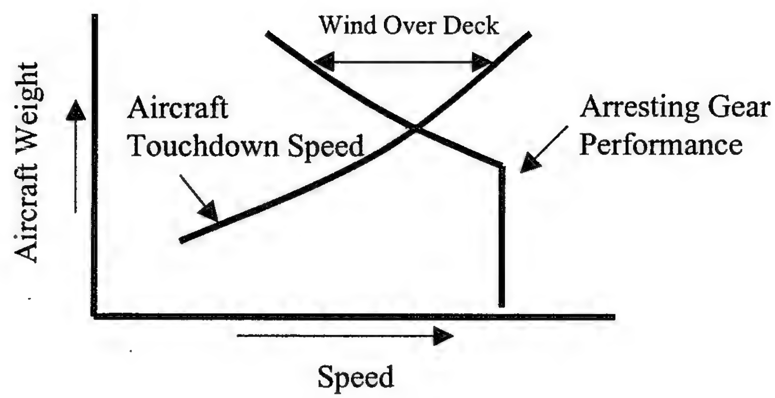
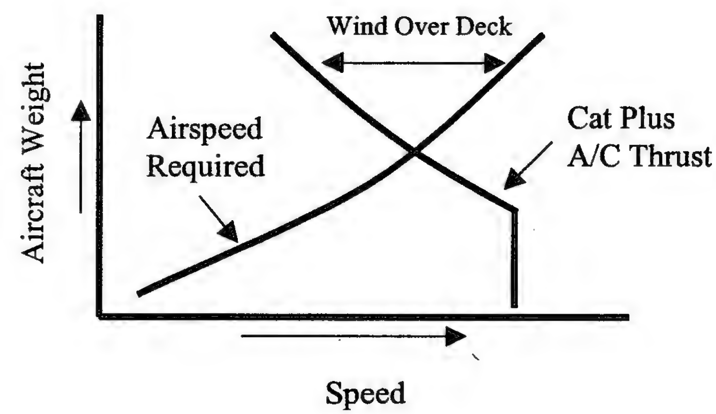
# Wind Over Deck

## Recovery Wind Over Deck




## Launch Wind Over Deck




- Aircraft Touchdown Speed = 1.05 * Vapp
- Airspeed Required = Calculated Liftoff Speed
- Arresting Gear Performance Calculated at Limit Capacity

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# Breakdown of Responses to Describe a Vehicle

Top-Level requirements related to the mission

Design Variables, Economic Variable and Vehicle Attributes

***Response (i.e. GW)*** = function (Requirements, Vehicle Characteristics, $k_{TP}$, $k_{TM}$)

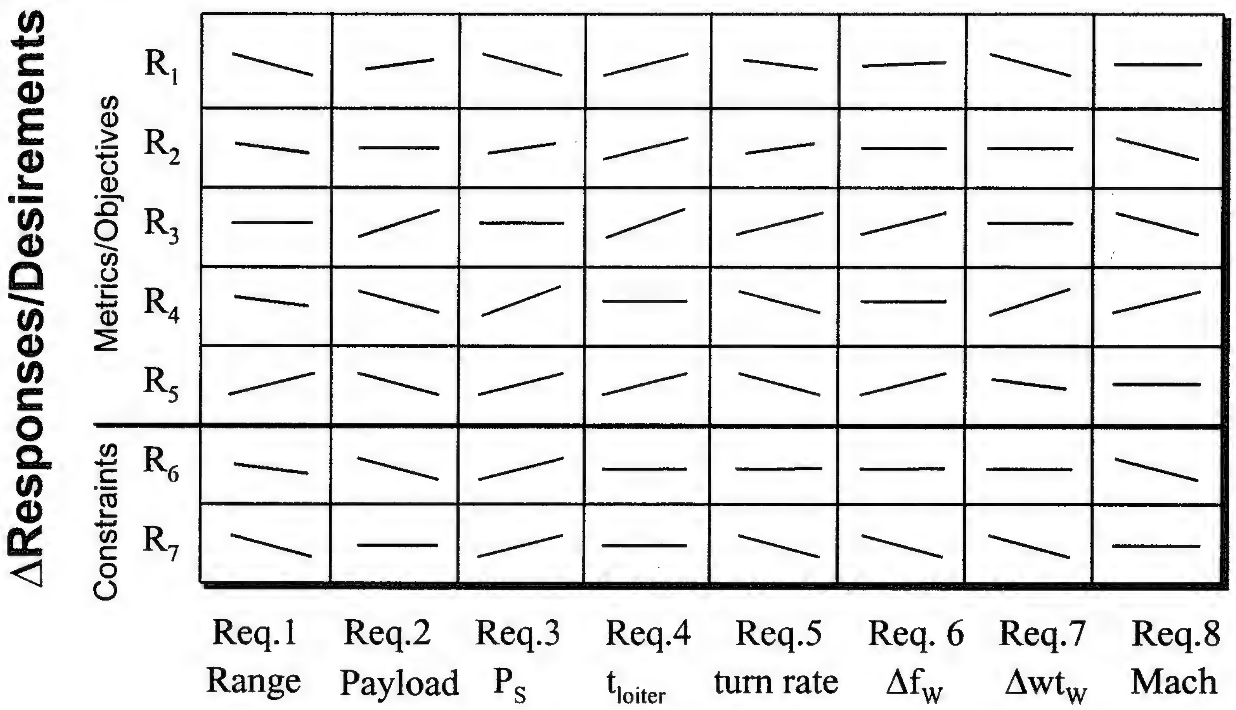
Technology k-factors (related to performance and to manufacturing)

- To cope with this large problem, evaluate it in "*snapshots*", where most inputs are held constant while a subset of the inputs varies
- This approach allows the consideration of mission requirements and applied technologies along with the geometry of the vehicle
- Snapshots 1,2,3 provide "deltas" in responses wrt baseline

**Use Response Surface Method once again !**

# Responses and Top Level Requirements

Snapshot 1




Example Responses:

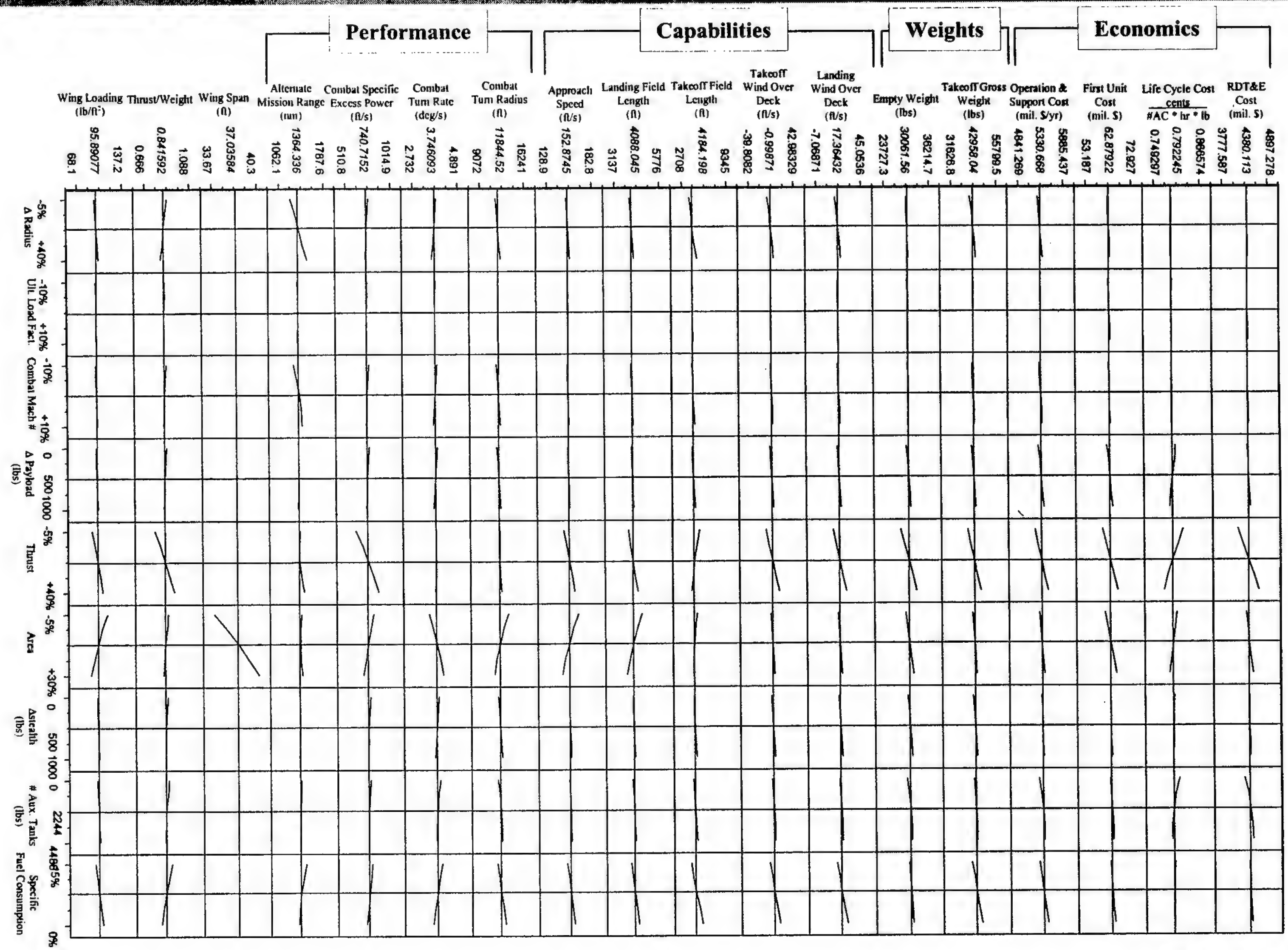
Gross Weight
Probability of Survival
Lethality
O+S
Acquisition Cost

Approach Speed (constraint)
TOFL (constraint)

T/W and W/S may belong in either the requirements or the responses section - depending on how the programs are set up

This approach de-emphasizes the geometry of an aircraft, and instead focuses on the mission requirements. However, it does require a baseline aircraft configuration. **Geometry and Technologies are fixed,** while Requirements vary. Each vector of top level requirements maps to a specific mission.

# *Requirement* RSEs for Notional F/A-18C

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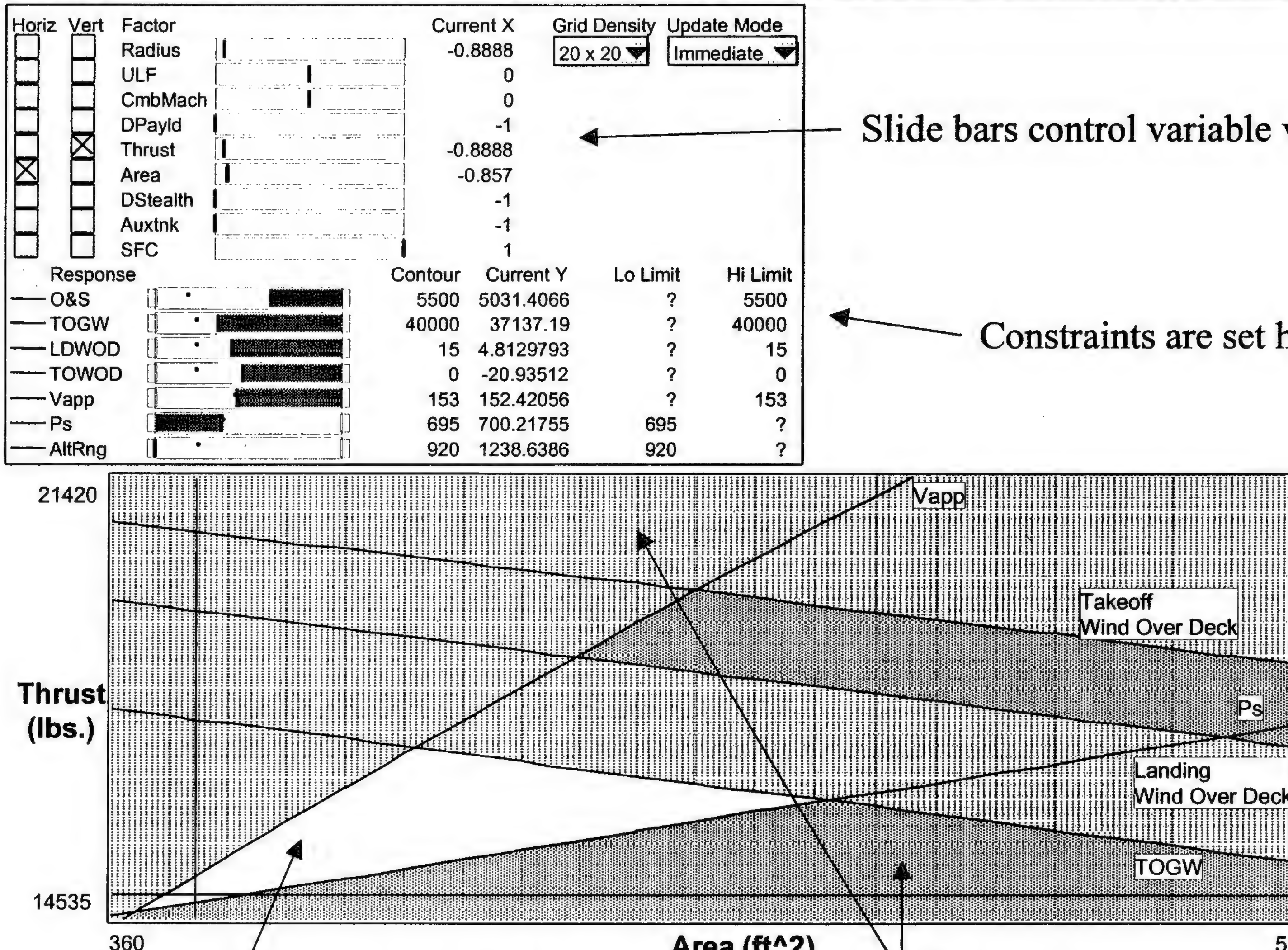
# Requirements Exploration: F/A-18C Design Contours

Response contours may be set here




Slide bars control variable values

Constraints are set here

White area indicates available design space, while filled areas indicate areas which violate set constraints

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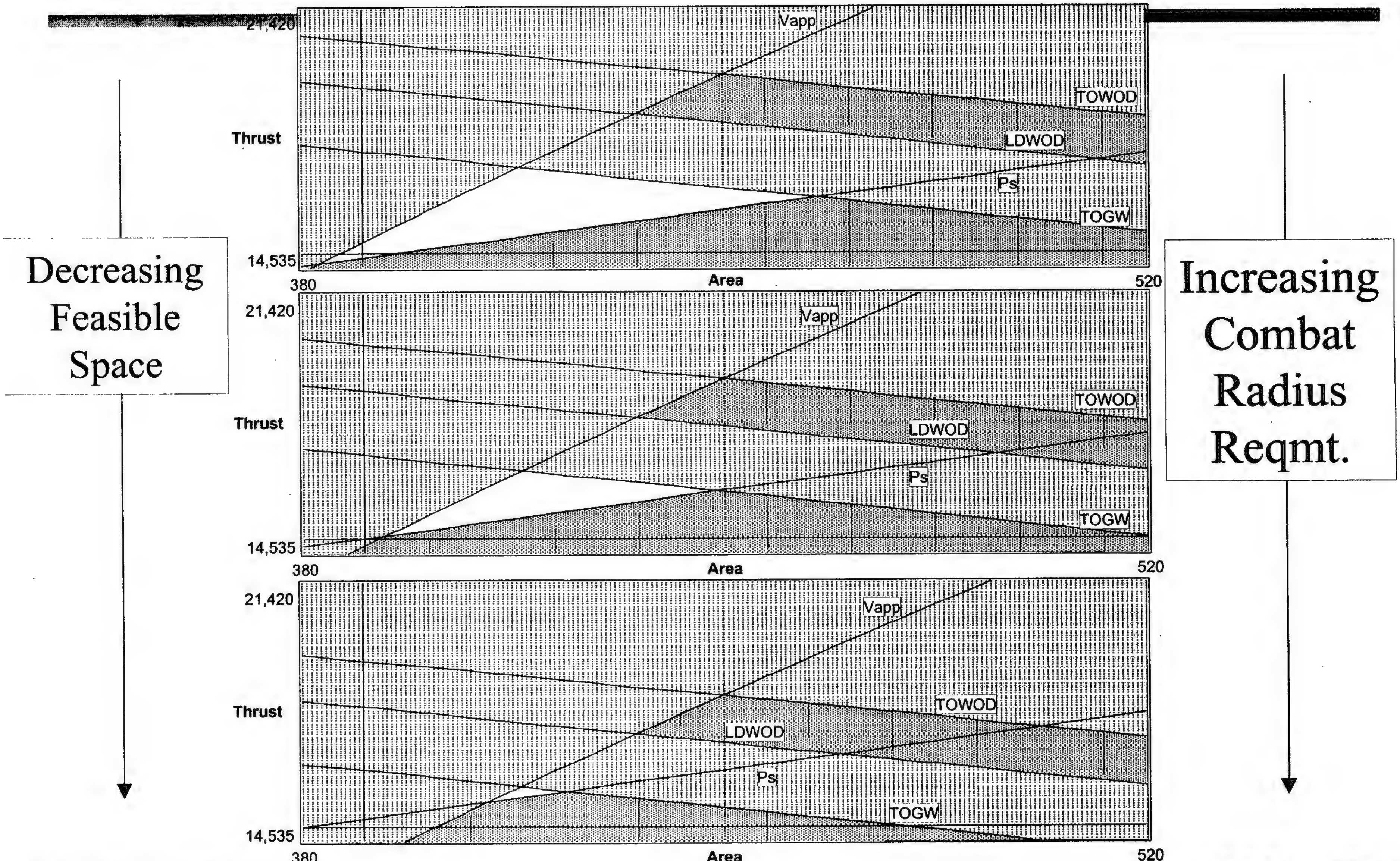
# Effects of Increase in *Combat Radius Req.*

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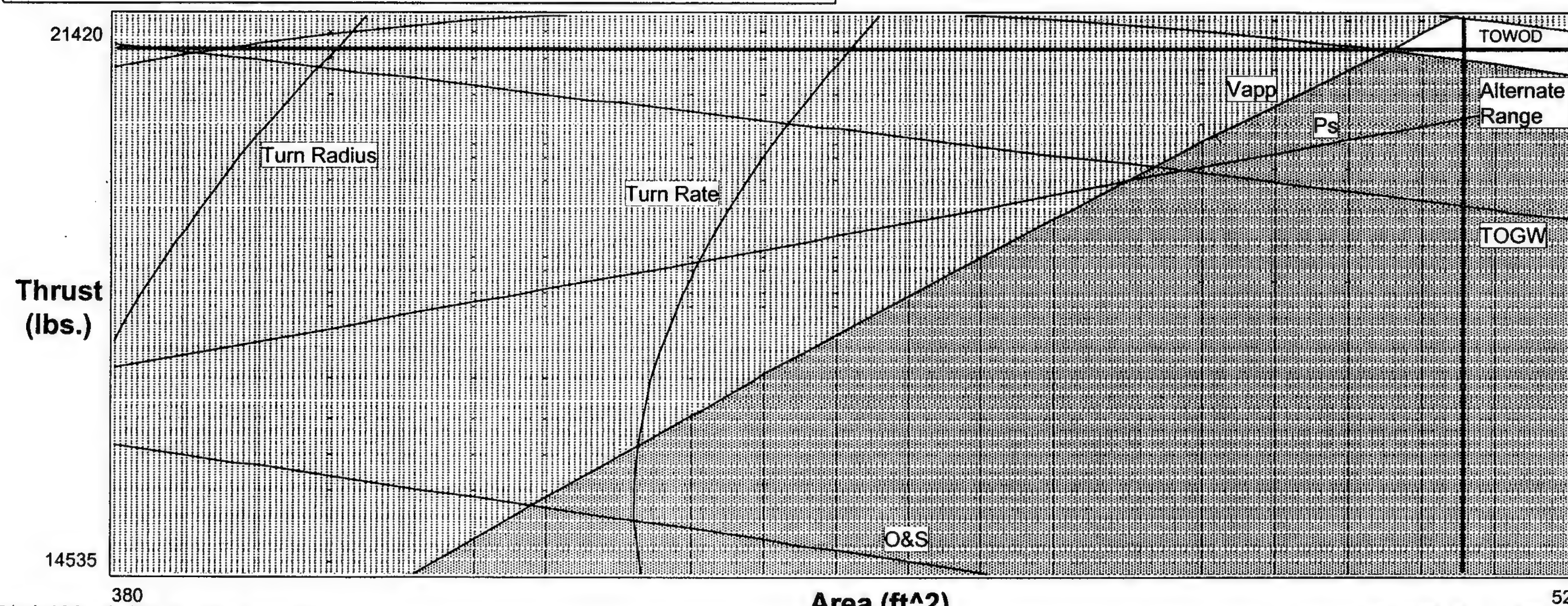
# Exploring the Space: Capturing the F/A-18E/F !

| Horiz | Vert | Factor | Current X |
|---|---|---|---|
| | | Radius | 0.964 |
| | | ULF | 0.71 |
| | | CmbMach | 0 |
| | | DPayld | -1 |
| | X | ~~Thrust~~ | ~~0.88888~~ |
| X | | Area | 0.857 |
| | | DStealth | -1 |
| | | Auxtnk | -1 |
| | | SFC | 0.3333 |

Grid Density: 20 x 20

Update Mode: Immediate

| Response | Contour | Current Y | Lo Limit | Hi Limit |
|---|---|---|---|---|
| O&S | 5130 | 5475.7833 | ? | ? |
| TOGW | 45000 | 47224.344 | ? | ? |
| LDWOD | 30 | 26.563468 | ? | 30 |
| TOWOD | 15 | 13.613377 | ? | 15 |
| Vapp | 151 | 150.2058 | ? | 151 |
| t_Radius | 12656.5 | 10828.741 | ? | ? |
| t_Rate | 3.8115 | 4.0987387 | ? | ? |
| Ps | 780 | 807.60615 | 780 | ? |
| AltRng | 1540 | 1545.1224 | 1540 | ? |

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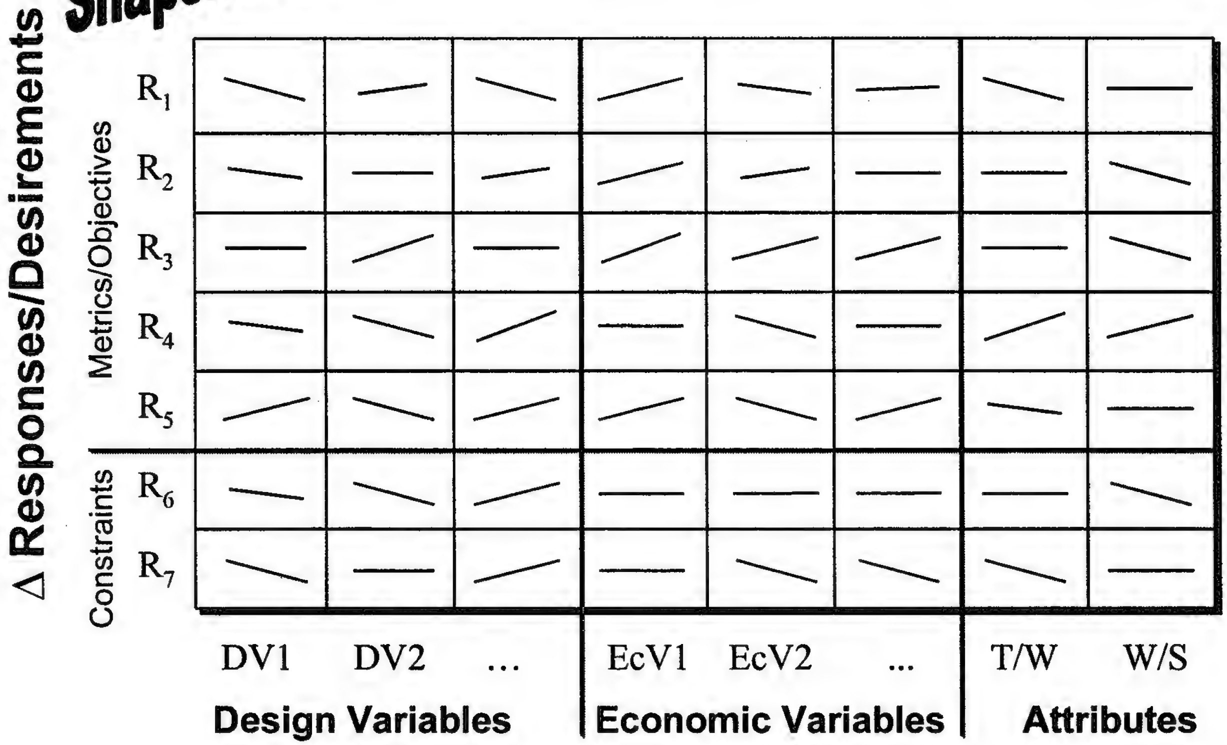
# Responses vs. Vehicle Characteristics

## Snapshot 2




**Vehicle Characteristics**

Geometry/Attribute relationship:

Turbine Inlet Temperature (TIT)

Specific Fuel Consumption (SPC)

Engine Cycle Variables

Level of Abstraction

Here, the **Requirements and Technologies are fixed**, but the vehicle characteristics are allowed to vary. Each vector of Design Variables, Economic Variables and Attributes maps to a specific geometry of a configuration.

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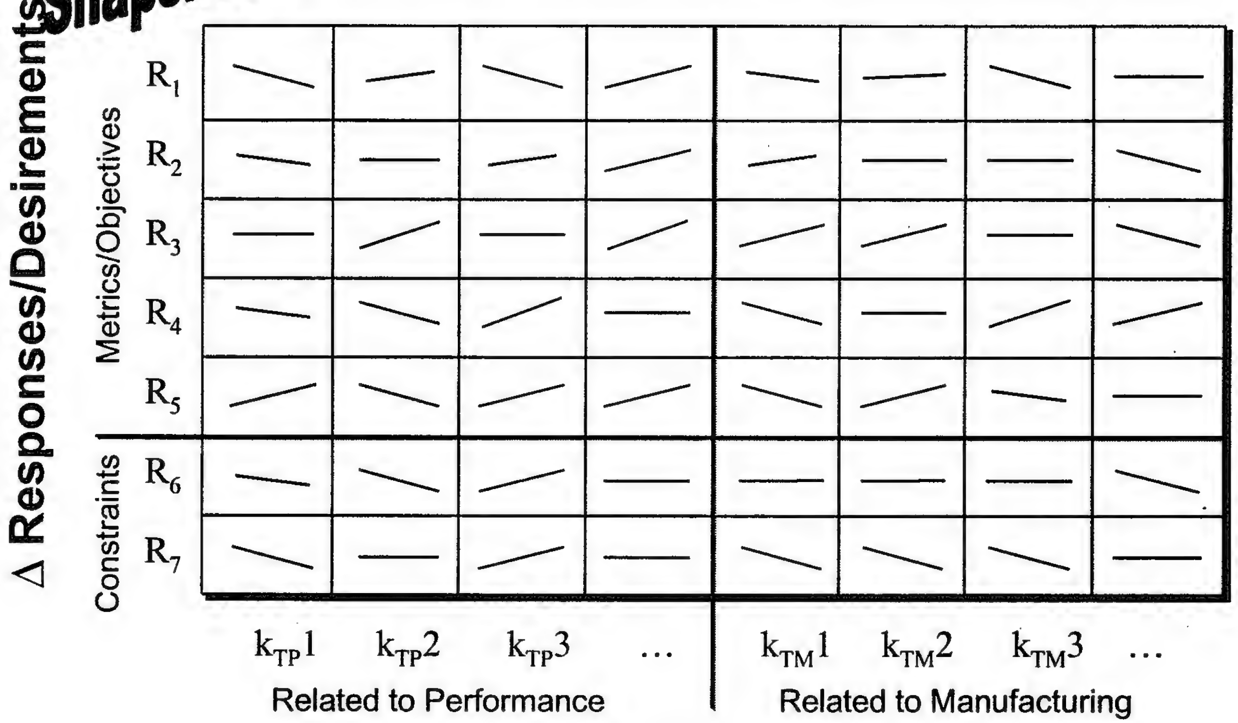
# Responses vs. Technology k-factors

Snapshot 3



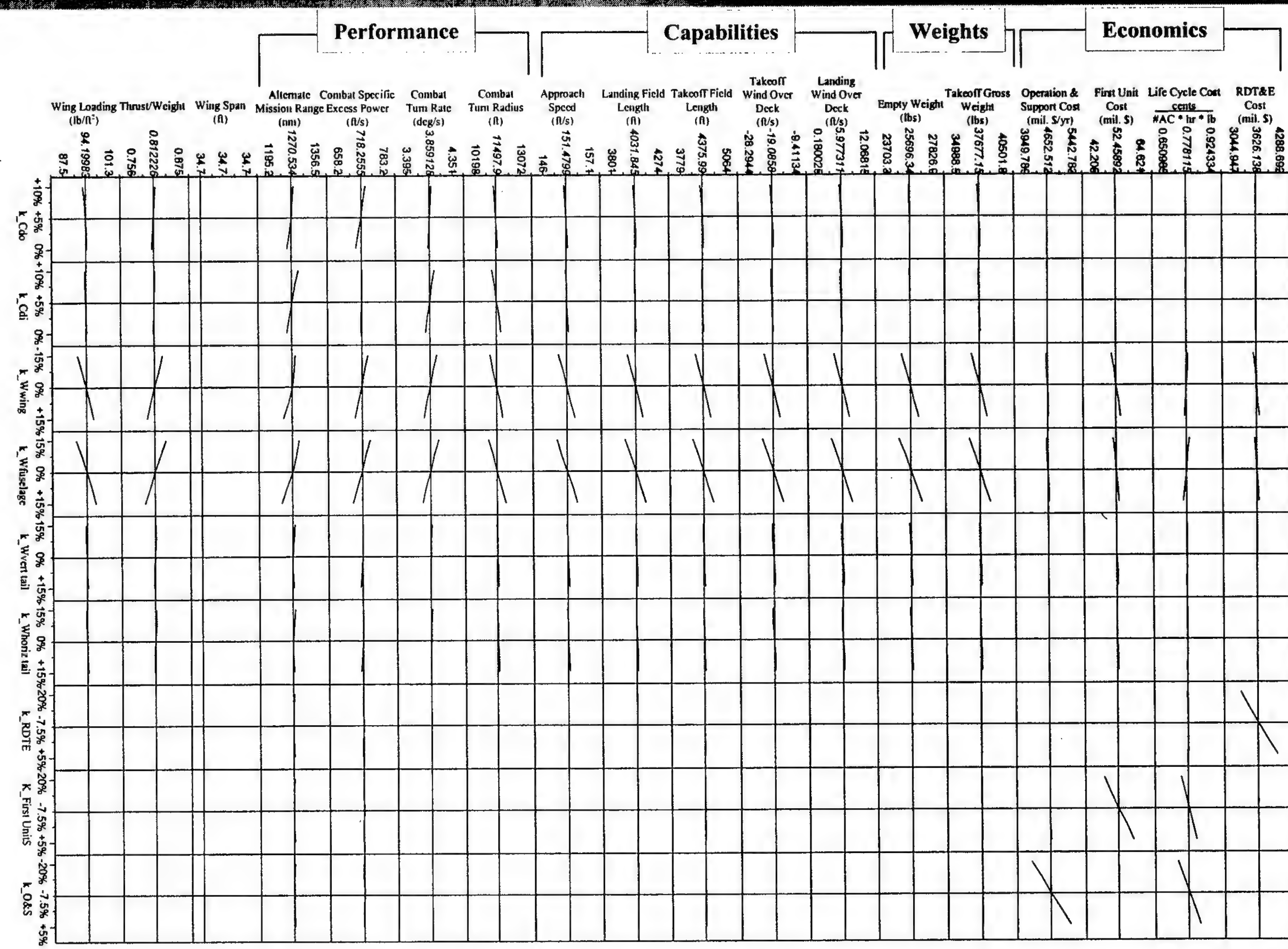

**Technology k-factors**

Technology k-factors are expressed in Δ%, compared to a baseline set of technologies

This is also known as the ***TIF*** (Technology Impact Forecasting) environment

Here, the **Requirements and the Vehicle are fixed**, but the technologies are allowed to vary. Each vector of technology k-factors maps to a specific combination of applied technologies.

# *Technology* RSEs for Notional F/A-18C

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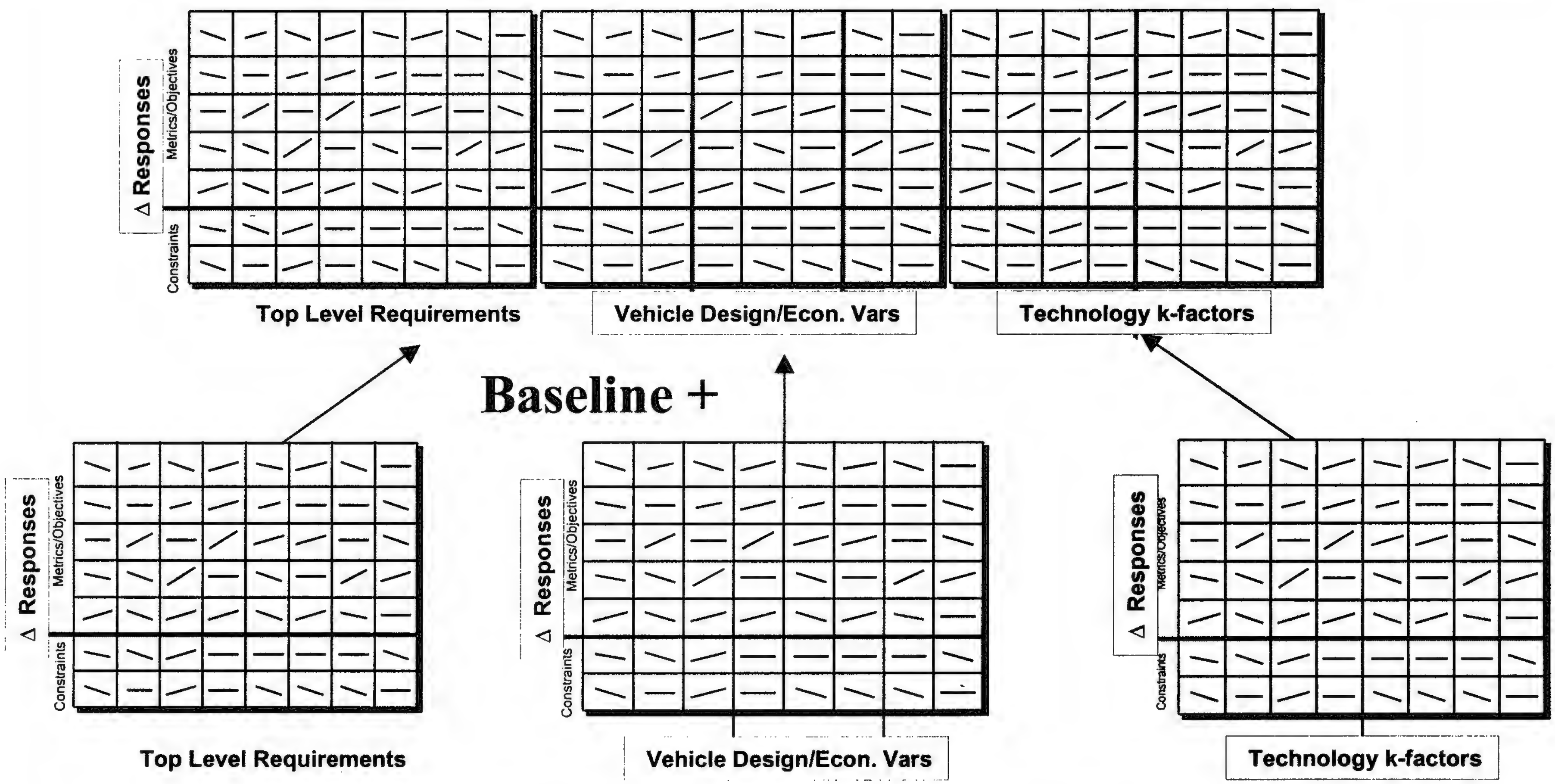
# Additive Creation of the Overall Environment




Assumption: Interactions among the input variables exist only within each group
(Or regroup the inputs to eliminate interaction across subspaces)

# Additive Creation of the Overall Equation

Fix all other groups (vehicle and technologies) and let only one group (requirements) vary

$$\Delta GW = (b_0)_R + \sum (req.1, req.2, req.3, \ldots)$$

Fix all other groups (requirements and vehicle) and let only one group (technologies) vary

$$\Delta GW = (b_0)_{Tech} + \sum (k_{TP1}, k_{TP2}, \ldots, k_{TM1}, k_{TM2}, \ldots)$$

***Response (i.e. $\Delta GW$)*** = function (Requirements, Vehicle Characteristics, $k_{TP}$, $k_{TM}$)

Fix all other groups (requirements and technologies) and let only one group (vehicle characteristics) vary

$$\Delta GW = (b_0)_{Veh.} + \sum (DV1, DV2, \ldots, EV1, EV2, \ldots, Attr1, Attr2, \ldots)$$

***Then:***

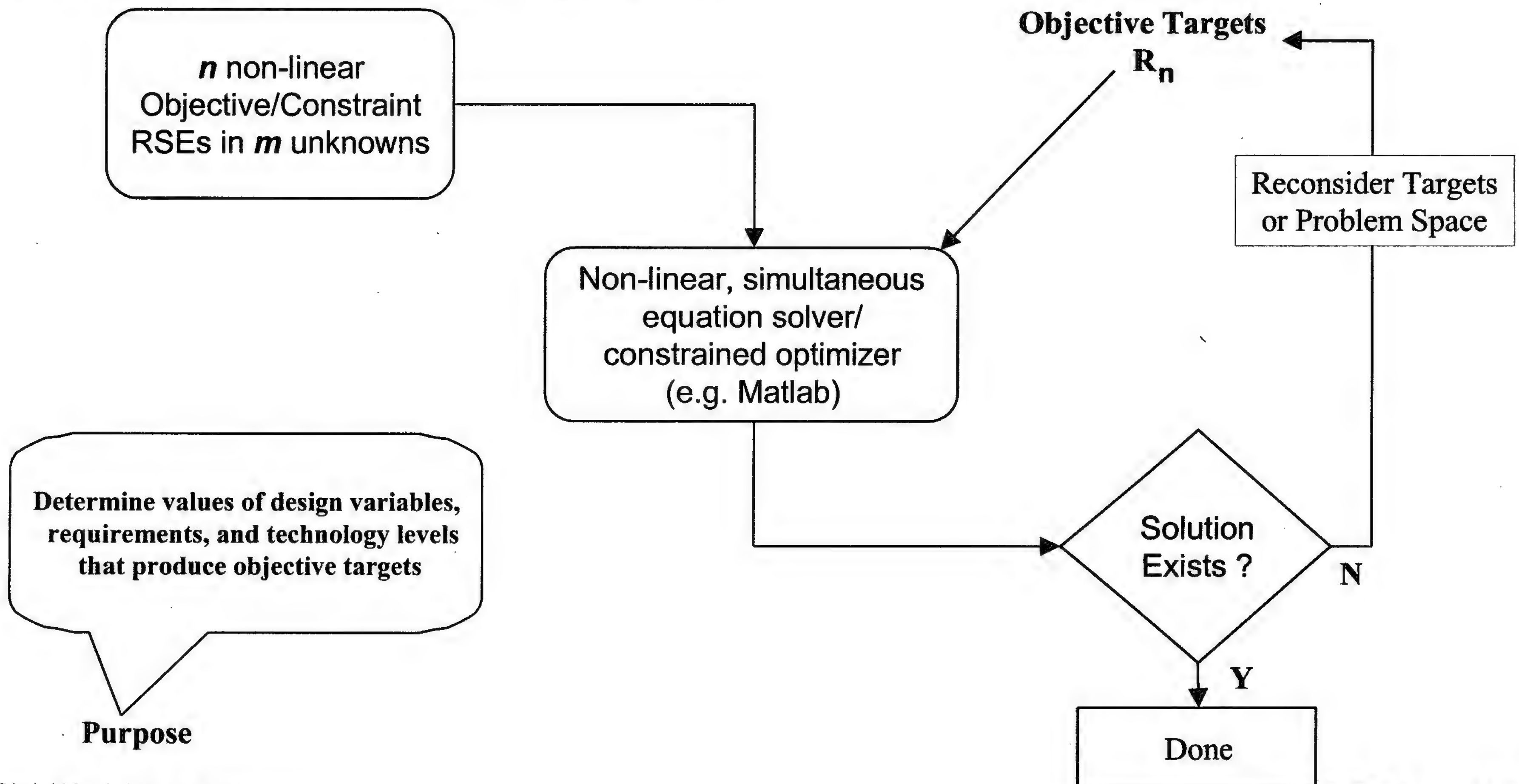
$$GW = (b_0)_{overall} + \sum (req_1, req_2, req_3, \ldots) + \sum (DV_1, DV_2, \ldots, EV_1, EV_2, \ldots, Attr_1, Attr_2, \ldots) + \sum (k_{TP1}, k_{TP2}, \ldots, k_{TM1}, k_{TM2}, \ldots)$$

This equation can now be re-solved for any parameter that might be of interest

# Is there a Solution??

**The set of coupled, non-linear RSEs can be used to determine if a solution exists for given metric targets**

$$R_i = (b_0)_{overall} + \sum(req_1, req_2, req_3, \ldots) + \sum(DV_1, DV_2, \ldots, EV_1, EV_2, \ldots, Attr_1, Attr_2, \ldots) + \sum(k_{TP1}, k_{TP2}, \ldots, k_{TM1}, k_{TM2}, \ldots)$$





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# One Example Application on the Notional F/A-18C

## Objective:

*Minimize the Gross Weight of a multirole fighter (Notional F/A-18C baseline)*

## Equality Constraint:

*Required Primary Mission radius = 357 nm (+15% from baseline)*
*Required Delta Weight for Stealth = 500 lbs.*

## Inequality Constraints (deltas with respect baseline):

$\Delta$AltRng $\geq$ 4%, $\Delta$OEW $\leq$ -4%, $\Delta$\$O&S $\leq$ -3%, $\Delta P_s \geq 2\%$,
$\Delta$TurnRt $\geq$ 3%, $\Delta$TurnRad $\leq$ -3%, $\Delta$WOD $\leq$ -3 knots

## Free Variables:

Requirements: *Ult. Load Factor, Combat Mach, Payload, Thrust, Wing Area, Aux. Tanks*
Technology K-Factors: *Minimum Drag, Induced Drag, Wing Weight, Fuselage Weight, Vertical Tail Wt., Horizontal Tail Wt., \$RDTE, \$1st Unit Prod., \$O&S*

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# Screenshots and Example Results

## Results:

**Objective:**

ΔGW = -8.8%

**Inequalities:**

ΔAltRng = 6.9%

ΔOEW = -10.1%

Δ$O&S = -3%

ΔPs = 3.6%

ΔTurnRt = 4.8%

ΔTurnRad = 6.7%

ΔWOD = 6 knots


The constraints/objectives/targets can be quickly changed and the optimization re-executed

Analysis routines created in MATLAB©

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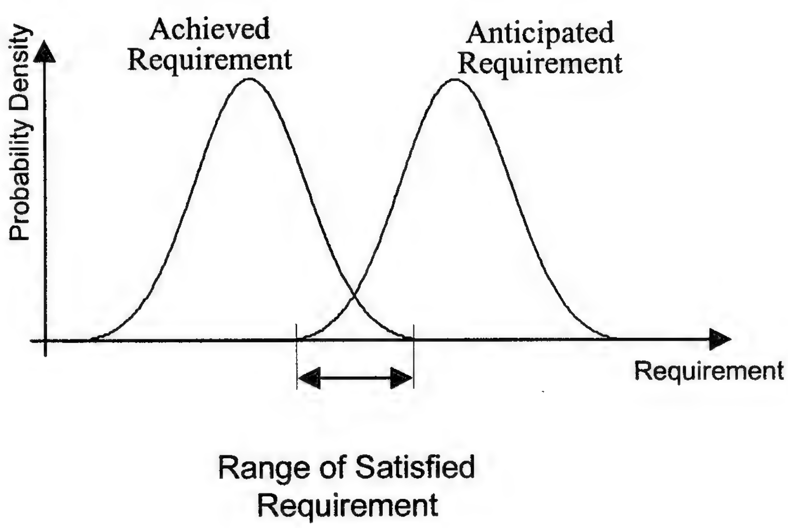
# Future……Incorporating Probabilistics: Achieved vs. Anticipated Requirements

### *One Requirement - 1-Dimensional Plot*




$P$(Satisfying Requirement)

$= P(\, \mathrm{Req}_{\mathrm{Anticipated}} - \mathrm{Req}_{\mathrm{Achieved}} > 0 \,)$

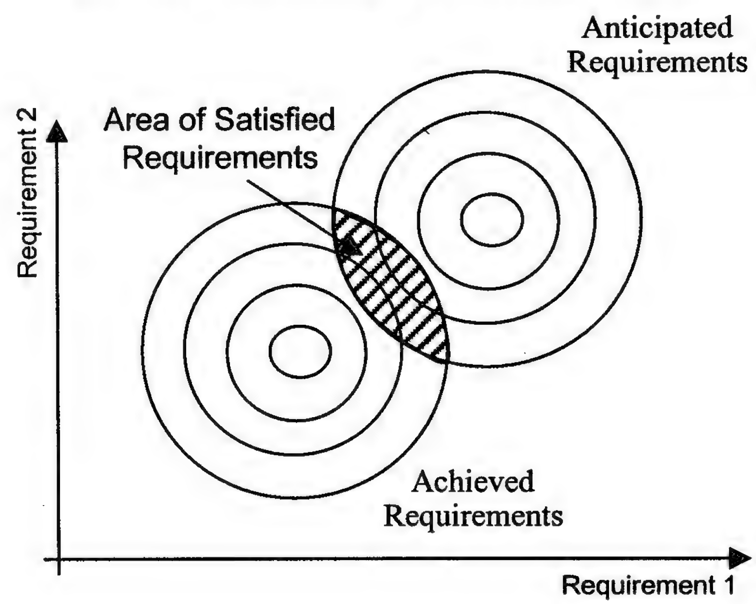
$= P(\, RD > 0 \,)$

$P(\text{Satisfying Requirements})$

$= P\left(\overline{\mathrm{Req}}_{Achieved} - \overline{\mathrm{Req}}_{Anticipated} > \bar{0}\right)$

$= P\left(\overline{RD} > \bar{0}\right)$

### *Two Requirements - 2-Dimensional Plot*





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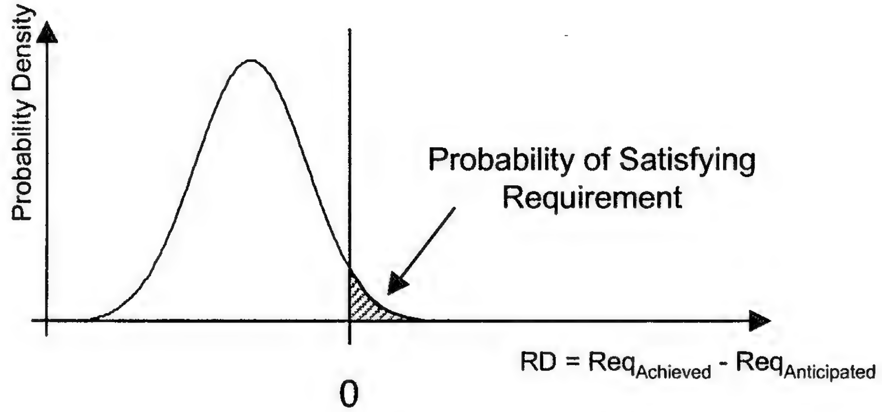
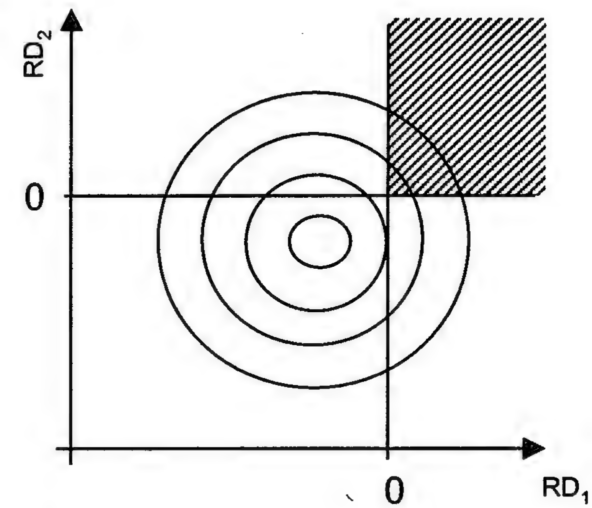
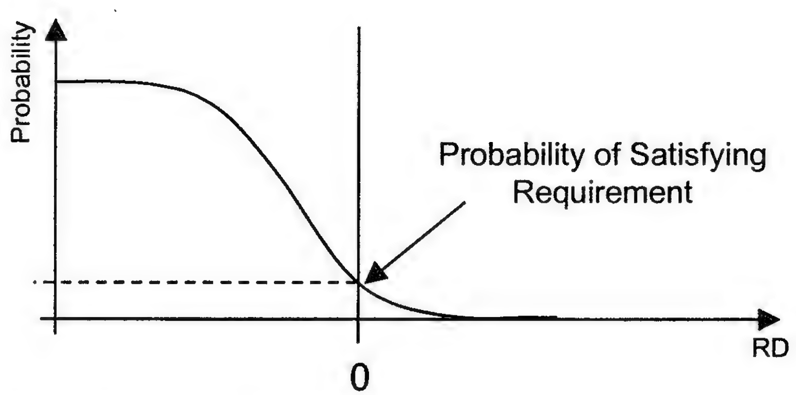
# Probability of Satisfying Requirements

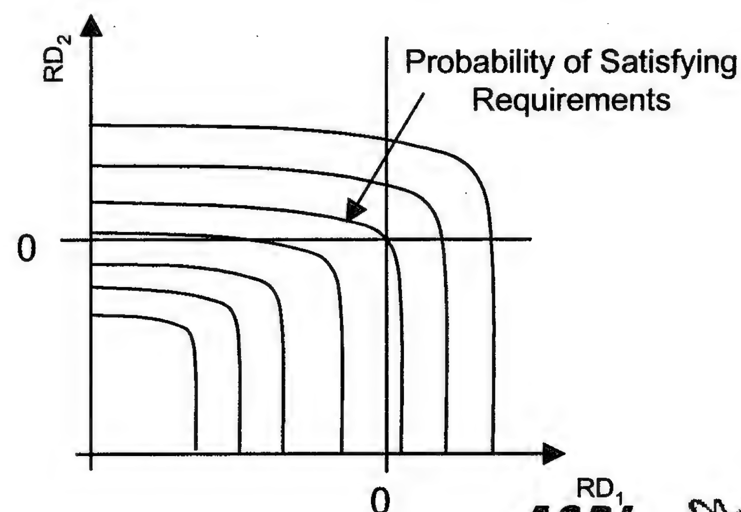
### *Probability Density Functions*




### *Cumulative Probability Functions*

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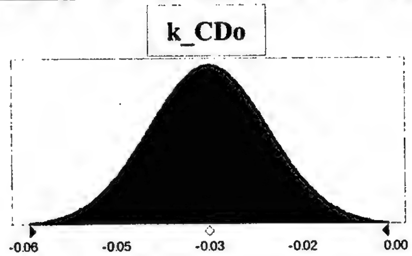
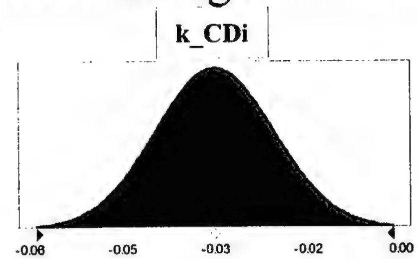
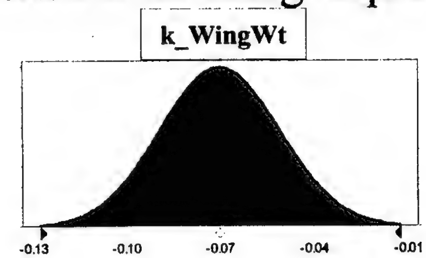
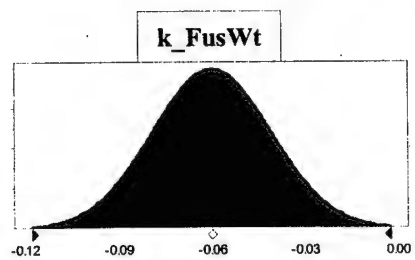
# Example: TOGW Req. for Notional F/A-18 (1)

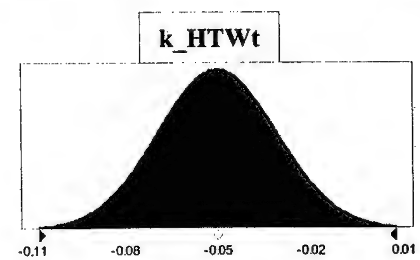
Scenario 1: Conservative tech. improvements gives low confidence of meeting requirement

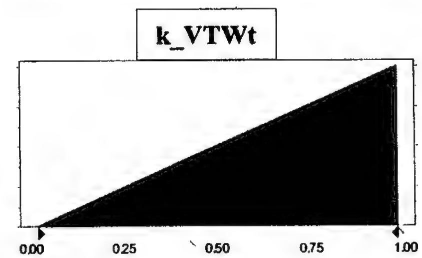


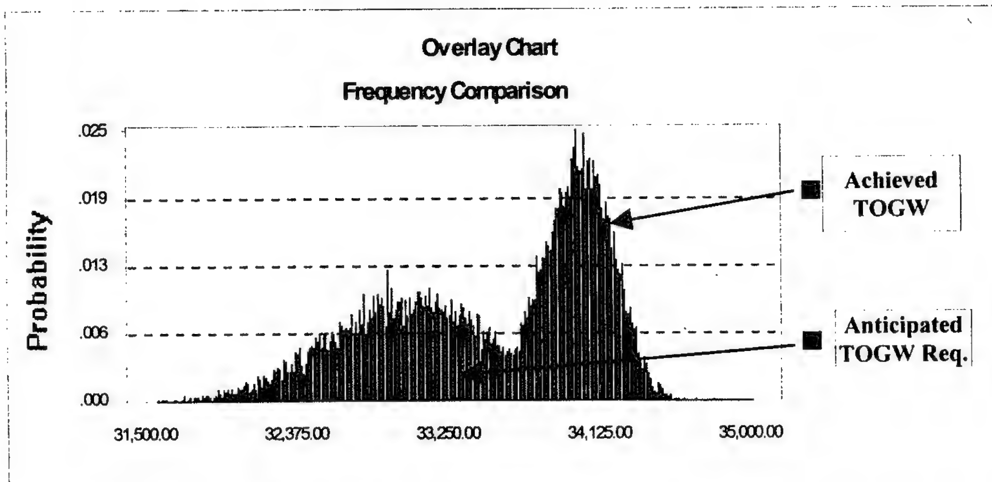



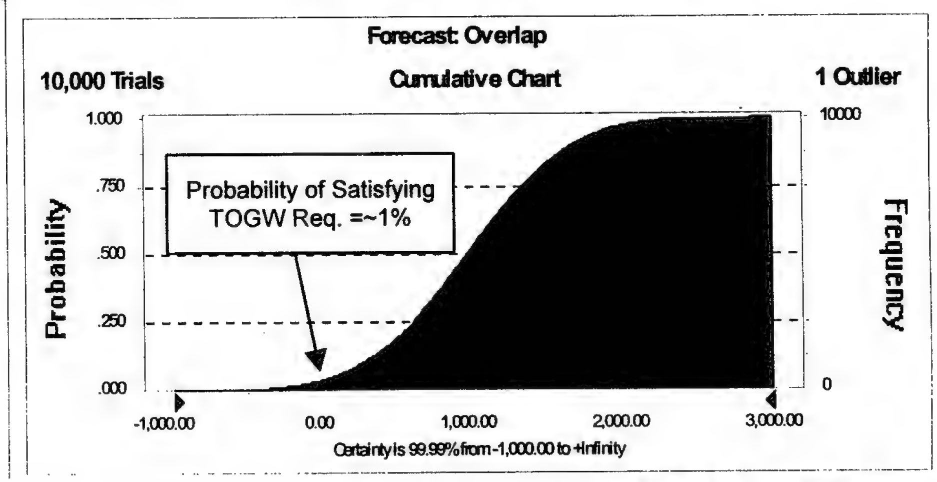

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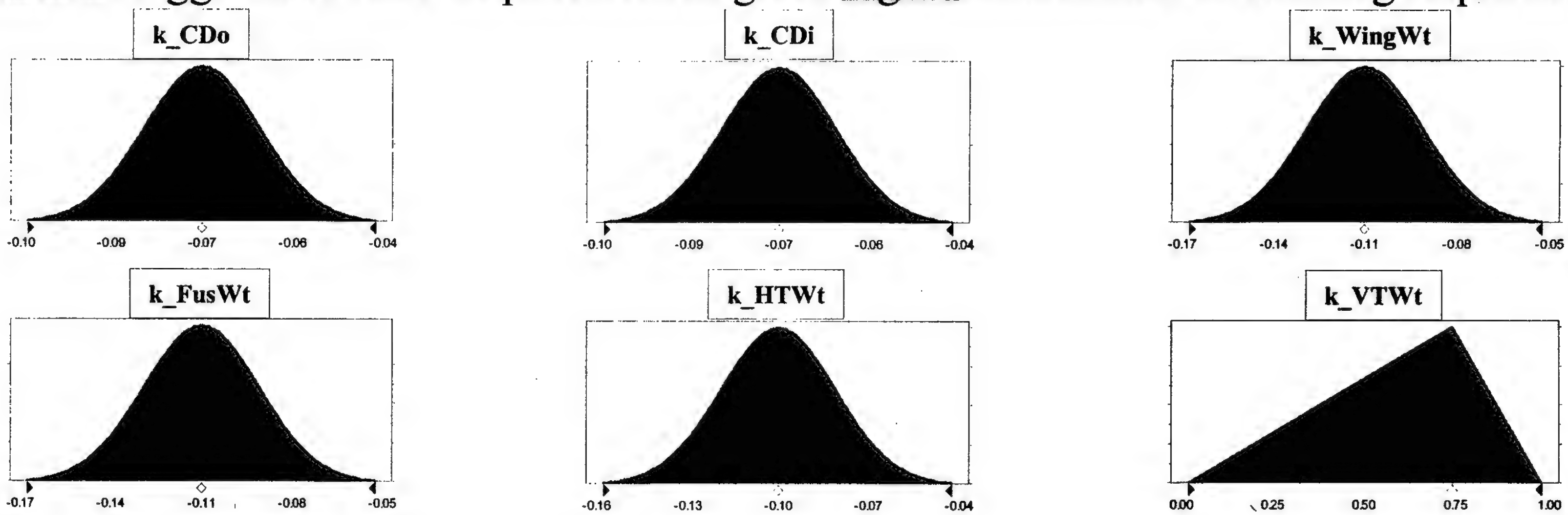
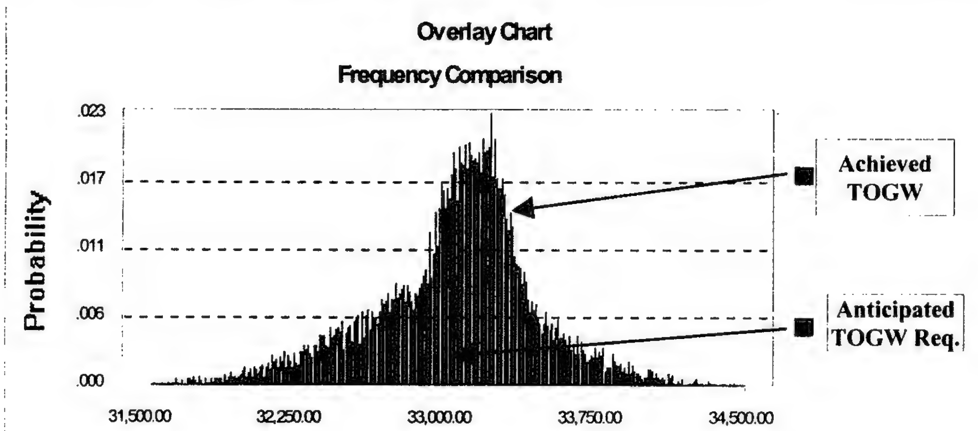
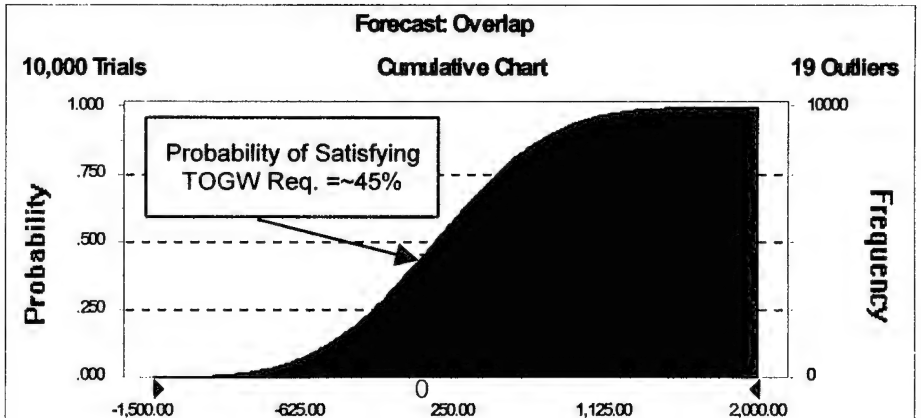
# Example: TOGW Req. for Notional F/A-18 (2)

Scenario 2: Aggressive tech. improvements gives higher confidence of meeting requirement





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# Section 4

1. *Introduction and Research Setting/Summary*

2. *Overall Technical Approach for Affordable Systems Design*

3. *Methods Implementation and Testbed Applications*

4. *Key Advancements in Method Components*

5. *Conclusions/Summary*

# Section 4

## Part B:
## Investigation of Advances in Soft Computing and Mathematical Sciences for Affordability Measurement and Prediction

# Tasks

- Main Tasks:
  - … development of a comprehensive database of key characteristics, relevant bibliographies, and clear identification attributes and limitations as to these techniques.
  - … for each examined technique, definitions, maturity status, data on leading scientists and organizations advantages and problems, software implementation, practical applications and 'pointers' to the problems to be addressed within the affordability science.
- Main Assumptions:
  - … customer's concept of affordability
  - … no more than 10 -15 areas and a certain period of time due to diversity and dynamism
- Results:
  - Comprehensive database of important modern mathematical techniques and their characteristics as applicable to affordability science.
  - Recommendations on use, limitations and desirable development of mathematical techniques with respect to affordability

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# Research Motivation?

- Find elements that can serve as a formal foundation for affordability science
- Selected the areas of investigation so as to have a broad range of application domain to address a wide variety of problems.
- Organize this broad range into categories and identify their primary area of concern on a higher level.
- Map critical areas in affordability science which would benefit from additional methods to the categories of solution techniques.

This will yield

⇨ The areas/categories which are the most critical to the affordability science on a higher level

⇨ A better understanding and greater insight as to where each of these techniques stands and

⇨ How they can be used to have the greatest positive impact on affordability science, and science and society in general.

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# Overview/Summary of Investigated Areas

| ***Method*** | ***Description*** | ***Applications*** |
|---|---|---|
| **Rough Sets** | Uncertainty Management<br>Upper and Lower Approximations | Uncertainty representation, knowledge analysis and analysis of conflicts, identification of data dependencies, Information-preserving data reduction |
| **Artificial Neural Networks** | Pattern Recognition and Function Approximation, Non-linear Regression | Approximate Reasoning, Pattern Recognition, Function Approximation, Time-Series Prediction |
| **Genetic Algorithms** | Genetics and Chromosome representation , Evolutionary Algorithms | Global Optimization, Applicable to discrete variables and parameters, Genetic Representation |
| **Fuzzy Logic** | Fuzzy vs. Crisp<br>Uncertainty Representation<br>Approximate Reasoning | Representation of incomplete, uncertain or partially true knowledge, Knowledge Management; Approximate Reasoning |
| **Chaos Theory and Theory of Fractals** | Dynamical Systems<br>Fractal Structures | Dynamical Systems, Chaotic Behavior, Image Coding, Wavelets |
| **Granulation and Aggregation** | Granular Computation | Clustering, Approximate Classification, Optimization; Approximate Reasoning |
| **Game Theory** | Decisions players make in a well-defined game | Analysis of strategic concepts, Partial Prediction on partial knowledge, Decision Support |
| **Ordinal Optimization** | Ranking and Optimization Method | Optimization; Ranking, Selection of the 'best' |
| **Semiotics** | Signs similar to those used in natural languages | Analysis of language, Linguistic Concepts, Logic of Signs |
| **Knowledge-Based Systems** | Expert Systems,<br>Knowledge- or Rulebase,<br>Inference, Reasoning | Reasoning; Diagnostics, Certification, Design |

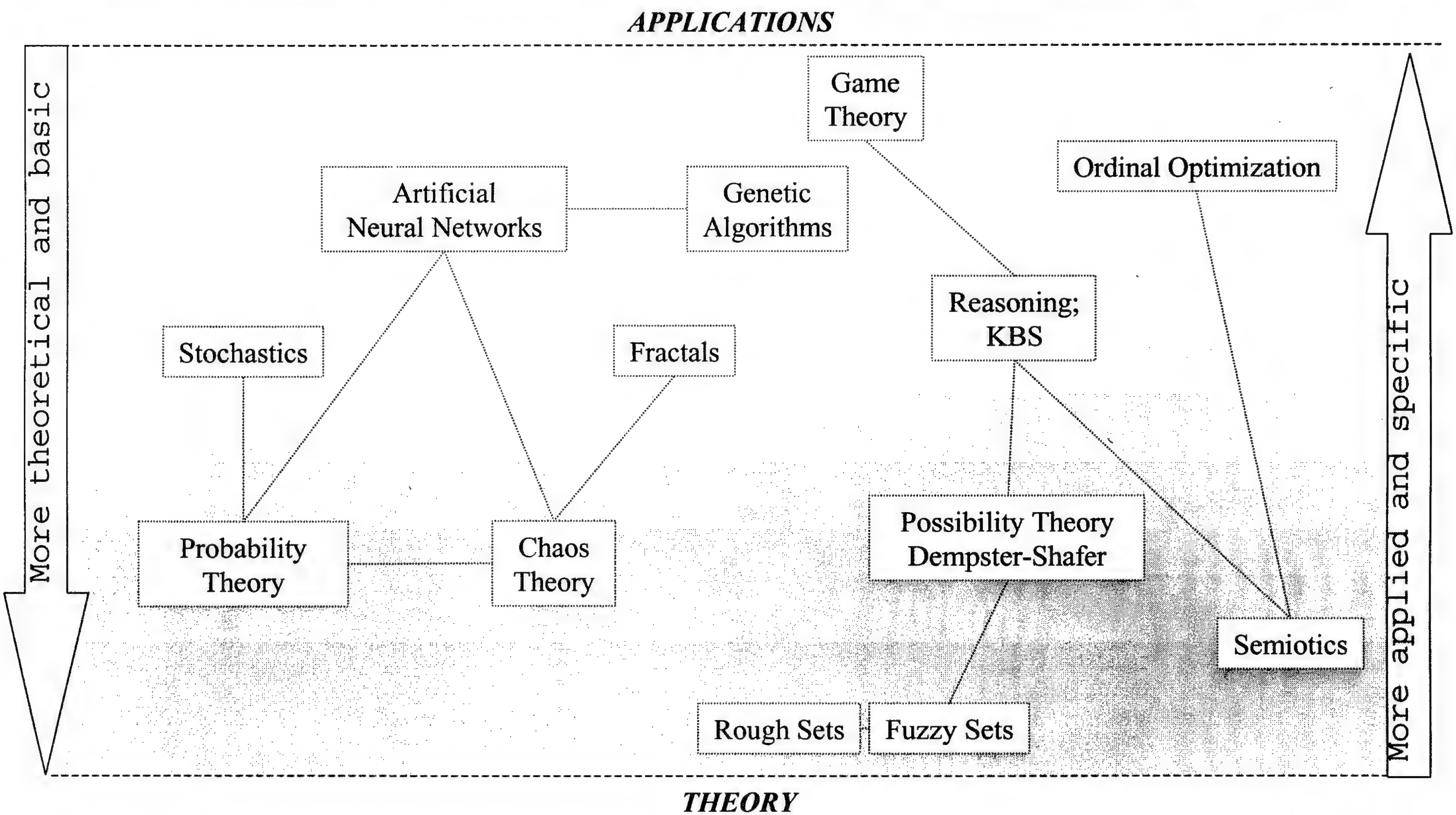
# Level of Application of a Method

- Ranks the techniques relative to each other between the two extremes
  - A may be more specifically tailored to an application or
  - A method encompasses fundamental and basic principles
- Compare only those on the same or a similar level of application
- Techniques on different or the same levels of application may build on each others principles or be integrated as hybrids
- Basic techniques with a low level of application are fundamental notions, they
  - generally require more work to be applied than those with high-level applications already specified and
  - can usually be applied to a much wider range of problems than high-level specific applications
- Techniques which evolve from a fundamental, basic stage to one or more high-level applications may all be known under the same name
- The Level of Application marks the first dimension in the classification scheme

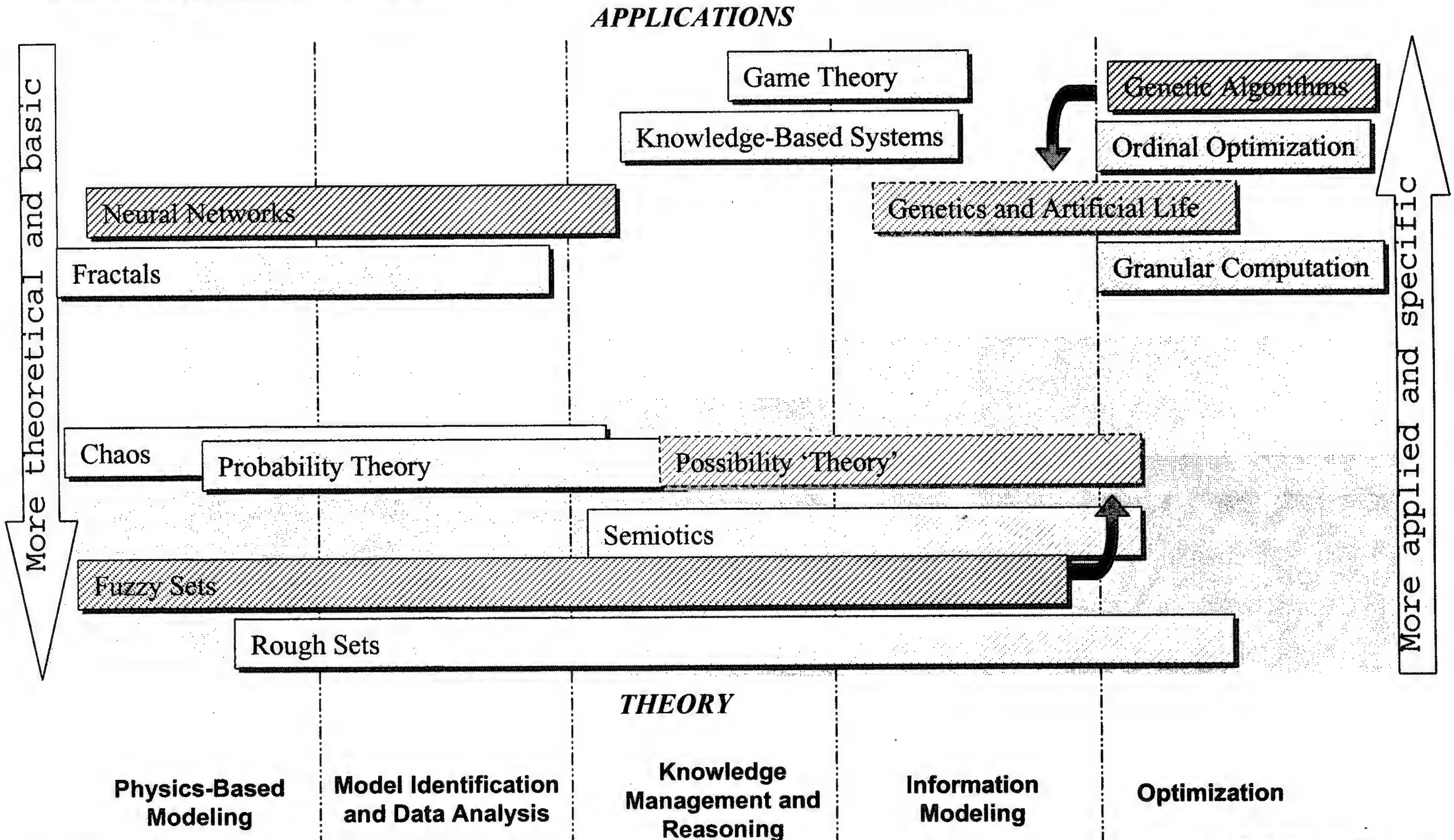
# How broad is the range from theory to application?
## A sample of techniques

| *Method* | *Description* | *Application Level* |
|---|---|---|
| • Artificial NN | Computational methods | procedure |
| • Chaos | Dynamical Systems | specific basic |
| • Fractals | Mathematical representation | specific basic |
| • Fuzzy Logic | Mathematical notion | basic |
| • Game Theory | Modeling Strategy Situations | application |
| • Genetic Algorithms | Discrete Optimization | application |
| • Aggregation/Granulation | Clustering and Optimization | basic, application |
| • Expert Systems | Reasoning | procedure |
| • Ordinal Optimization | Ranking Optimization | application |
| • Rough Sets | Mathematical notion | basic |
| • Semiotics | Signs and Language notion | basic |

# Where do these methods fit in?



# Areas of Focus and further investigation

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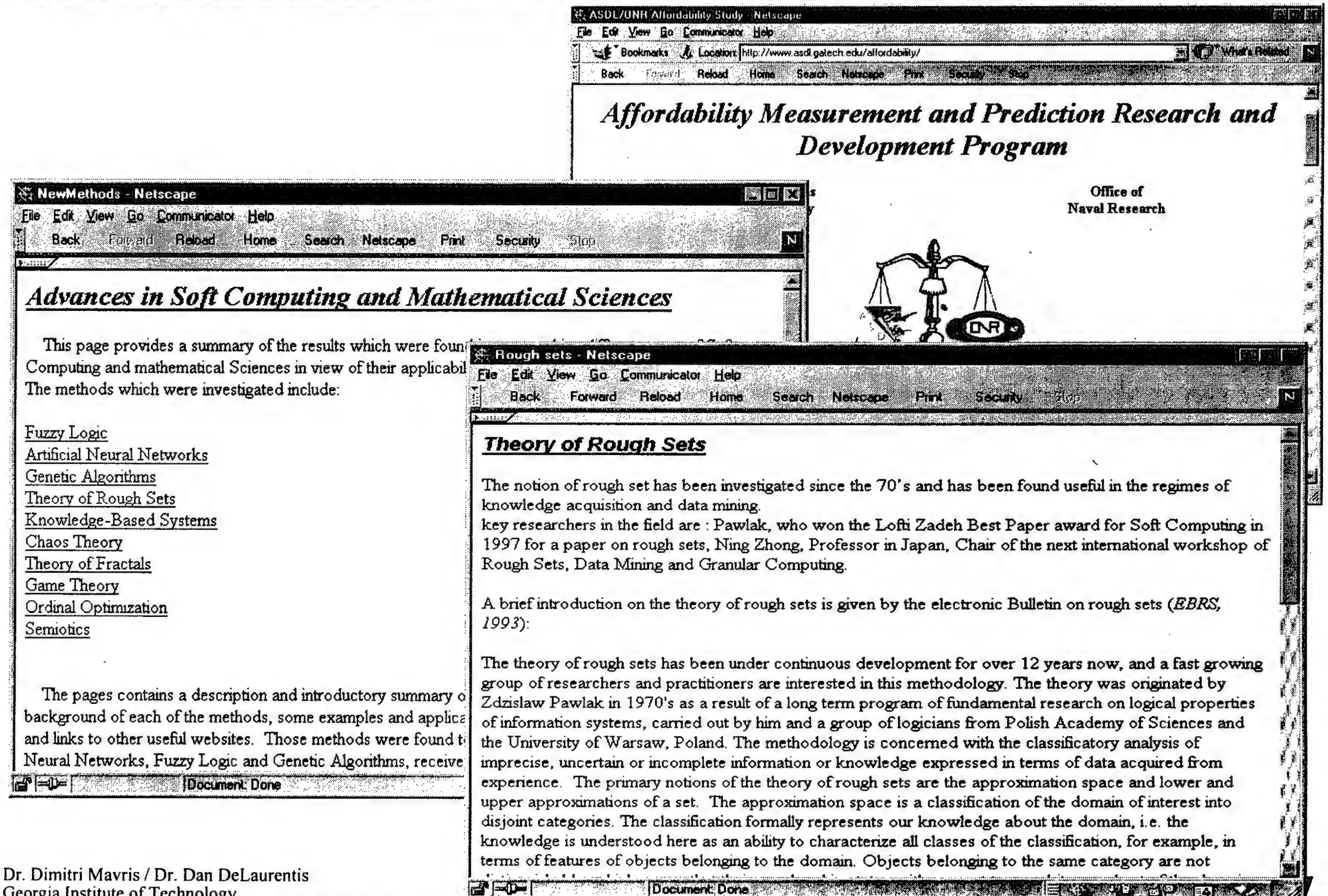
# Screenshot of the Summary Web Pages:

http://www.asdl.gatech.edu/affordability/newmethods/

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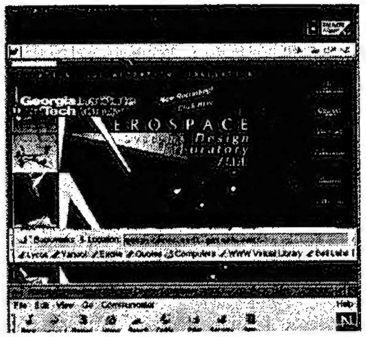
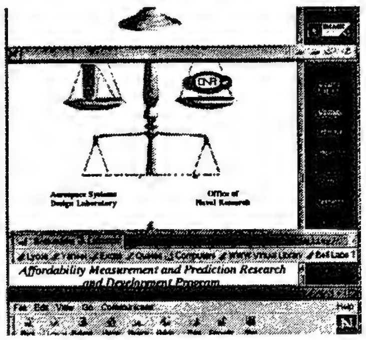
# Other Web Sites of Interest



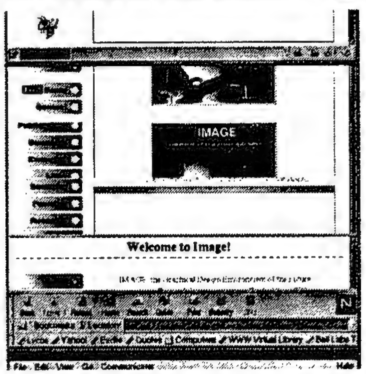

Aerospace Systems Design Laboratory

www.asdl.gatech.edu




ASDL Affordability Research

www.asdl.gatech.edu/affordability




ASDL Architecture Research

www.asdl.gatech.edu/image

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# Summary

- Database of methods and key characteristics
  - In electronic form, available on the web
  - Summary write-ups for each technique, addressing function, type of implementations and other summary information and characteristics
  - Reference Bibliography for each technique
- Method for classification of techniques according to 'dimensions', such as
  - Level of Application
  - Problem Domain in terms of decision making
  - Select Techniques to apply and give further consideration
- Application examples of:
  - Genetic Algorithms for Technology Impact Forecasting (high application level, optimization)
  - Artificial Neural Network for Metamodel-building (medium applicationlevel, function approximation)
  - Fuzzy Logic to Possibilistics for uncertainty management (basic, low application level with broad range)

# Section 4

# Part C: Stochastic Methods Research

# Stochastic Methods Task Summary

Main Objective: To define the requirements and identify the specific tools for the transition from a probabilistic decision-making mechanism for Affordability to a stochastic environment.

Specific Tasks:

- Establish the need of a time-varying model (current shortcomings)
- Identify the needed elements of a proper stochastic approach including mathematical tools, decision-making models, etc,
- Recommend ways that the environment assists (not hinders) the making of rational decisions (resource allocations)

# Why Stochastics ?

- Technology readiness changes in time
- Fidelity Uncertainty changes in time
- Customer requirements change in time
- Fitness landscapes (i.e. objective function surfaces) change in time
- Operational environment changes in time
- Budget allocations change in time

……. ***Bottom line***: *Both deterministic and probabilistic variables involved in identifying and designing affordable systems evolve in time. Stochastic methods are needed.*

# Analogies:
# Common Applications of Time Series Prediction

- Weather forecasting
- Sales forecasting
- Economic forecasting (i.e., price)
- Stock market forecasting
- Manufacturing forecasting
- Prognostic of incoming failures
- etc.

# Issue: Prediction of Stochastic Systems

What is time series prediction ?

- **Time series prediction -->** find the future values $\{x_{N+1}, x_{N+2}, \ldots\}$ Given $\{x_1, x_2, \ldots, x_N\}$, where $x_t$ is the series value sampled at time $t$.

- (Takens, 1981) If the series is deterministic, there exists $d$, $\tau$ and $f(\cdot)$ such that for every $t > (d \cdot \tau)$

$$x_t = f(x_{t-\tau}, x_{t-2\tau}, x_{t-d\tau})$$

Unfortunately, there is no exact method to find $d$, $\tau$ and $f(\cdot)$ when the series is too small (less than $10^d$ samples for $d$ and $\tau$)

# Shortcomings: Current Prediction Methods

- There are major weaknesses with current time-series methods need to be overcome:
  - Generally only valid for very short term prediction (i.e. can only predict next steps $x_{N+1}$, $x_{N+2}$)
  - Lack ability to incorporate *causality*, especially through reasoning/learning

- Studies under this grant focused on advanced time-series prediction methods. In particular, a neural-network model is under development for the prediction of airline load factor and fuel price based on historical data and cause/effect relationships

# The Classical Approach

Many time series can be modeled by two simple models

- Autoregressive (AR)

$$Z_t = \phi_0 + \phi_1 Z_{t-1} + \phi_2 Z_{t-2} + \ldots + a_t$$

- Moving average (MA)

$$Z_t = \phi_0 + \theta_1 a_{t-1} + \theta_2 a_{t-2} + \ldots + a_t$$

- Combination of two models (ARMA)

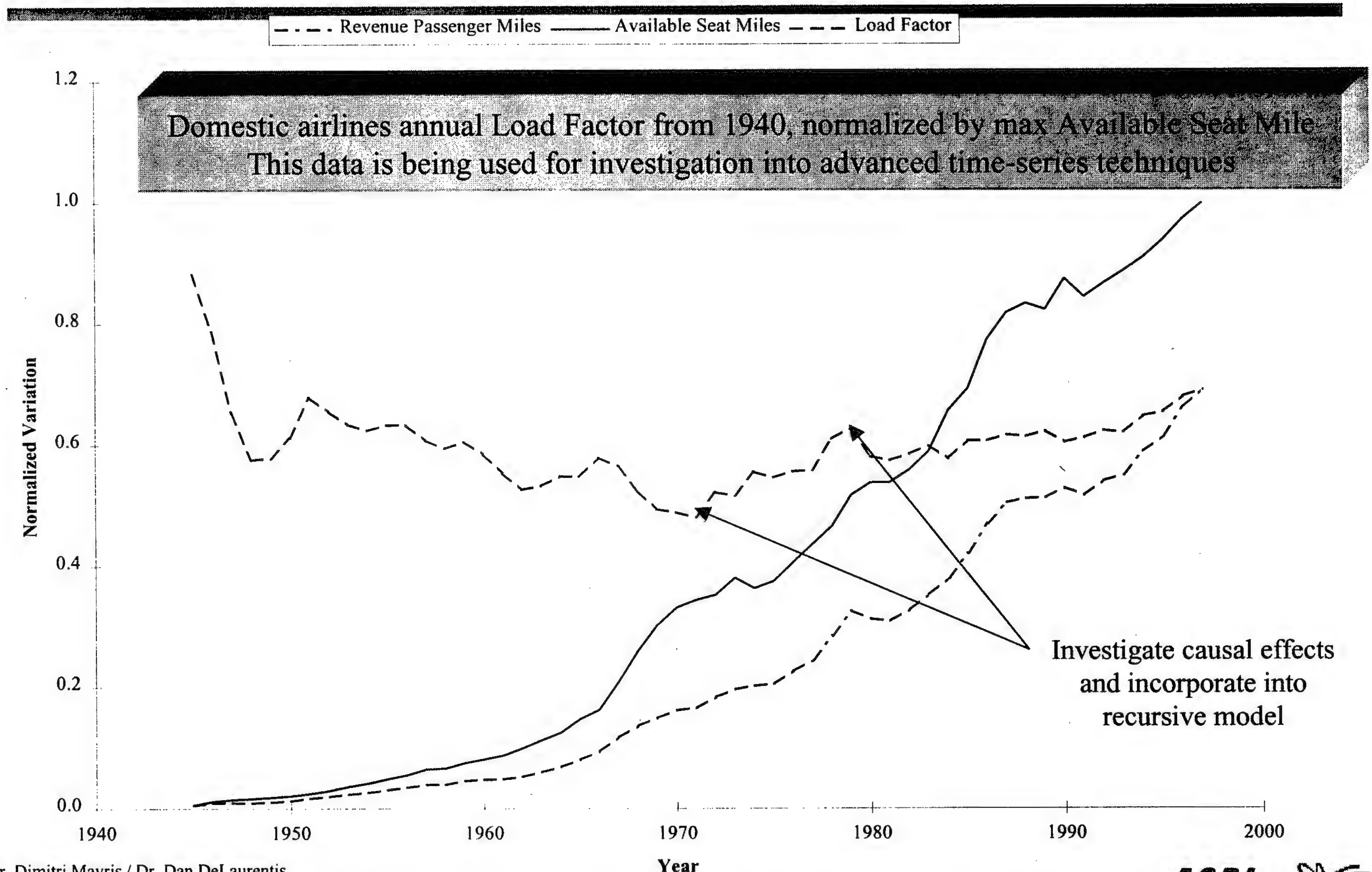
$$Z_t = \phi_0 + \phi_1 Z_{t-1} + \phi_2 Z_{t-2} + \ldots + \theta_1 a_{t-1} + \theta_2 a_{t-2} + \ldots + a_t$$

# Neural Network Approach

- (Hornik 1989) showed that neural networks can be used as universal function approximators.
- For time series prediction problems, let's assume we know $d$, $\tau$ and want to find $f(\cdot)$ using neural networks.
- For *nonstationary* time series prediction, the network must have *memory* that holds the past events and an associator that used the memory to predict

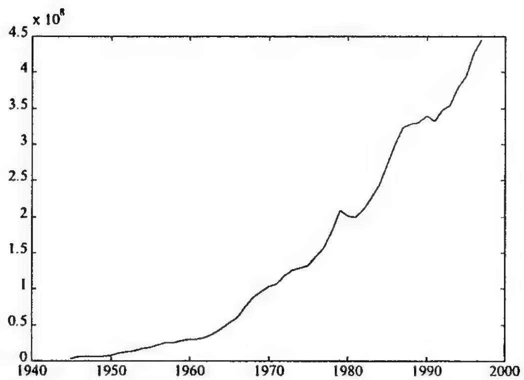
$$\mathbf{x}(t) \longrightarrow \boxed{\text{short-term memory}} \longrightarrow \boxed{\text{generic predictor}} \longrightarrow \mathbf{y}(t)$$

# Data Example



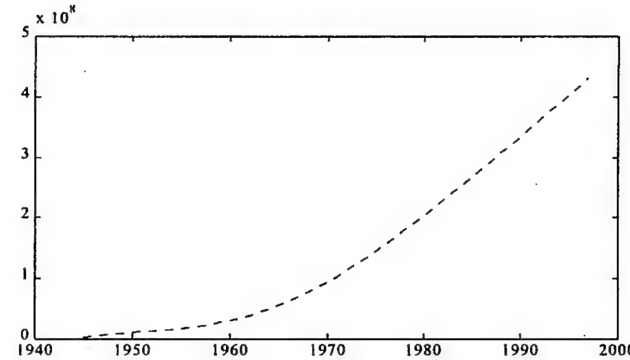
# Prediction of Revenue Passenger Miles

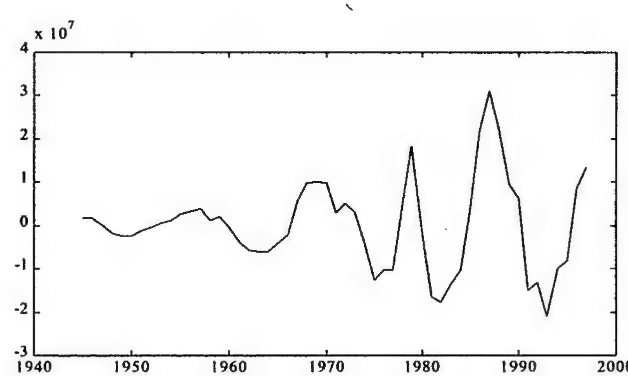
Feed-forward neural network results:




**Historical data**

**Trend**



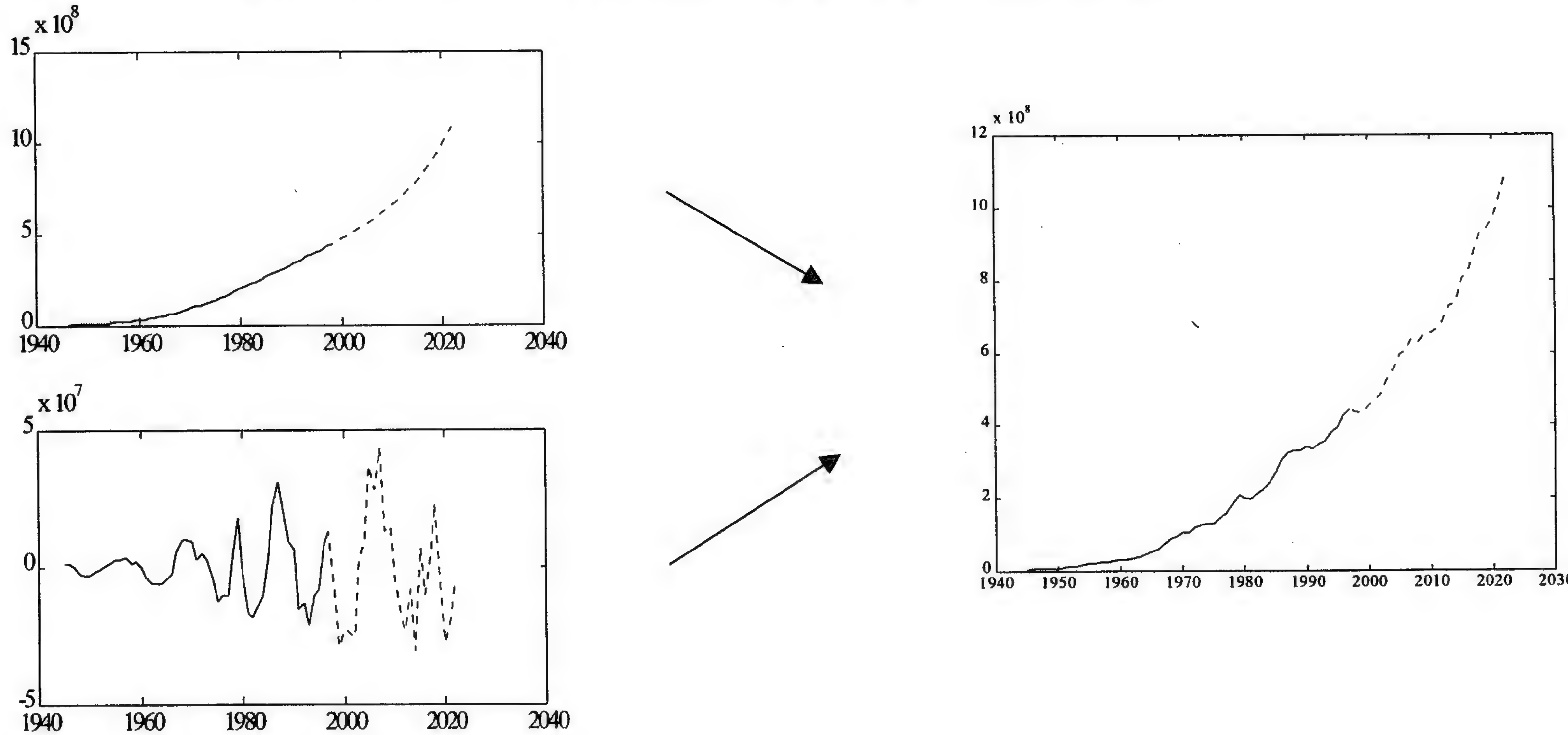




**Oscillating detail**

[redacted]

# RPM Prediction (cont.)

Feed-forward neural network results:
Trend can be captures, but without causal factors, oscillation for short term prediction is impossible



# Representation of Stochastic Processes

## Motivation

Information must be readily available at all times during decision-making processes

Information is stochastic and highly dynamic

Information must be easily transformed into knowledge

Information is distributed and very large amounts exist

## Research

Study methods for representing stochastic processes in the context of decision-making

## Findings

Evolutionary modeling techniques exist

Difficulty in identifying axis of change; area for future research

Results from ONR base research plays a key role in the structure of the information model

# Definitions in the Context of this Research

- Information

  *A collection of data describing products and processes.*

- Knowledge

  *Information in context.*

- Transaction

  *A valid action that has occurred.*

- Event

  *A transaction that happens at a specified time.*

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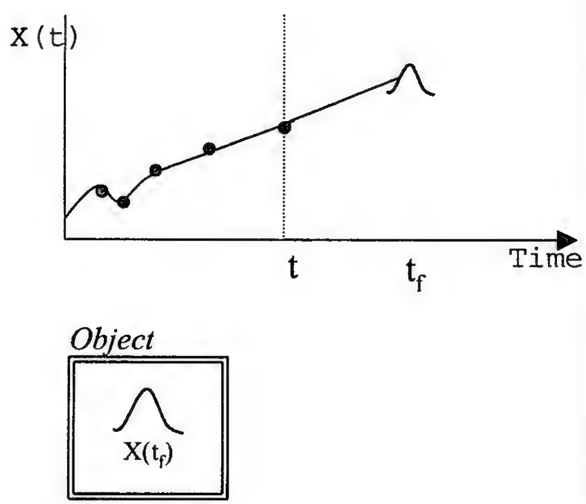
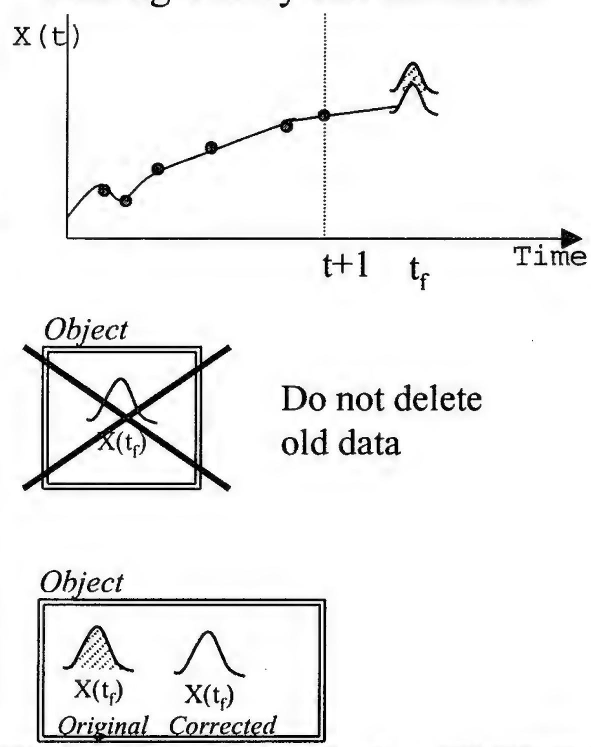
# Evolutionary Data Structures

- Current database technologies using linked-lists can be used to store forecasting information.

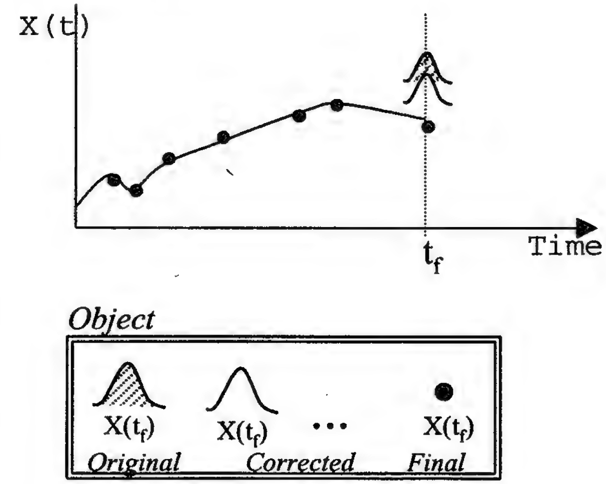
Distributions can be stored in objects and keyed to time →




Linked list structures can be used to store information as it evolves over time. This is needed so that decision-making history can be stored. →




Object must be able to store both stochastic history and discrete event as well as return appropriate result when queried.

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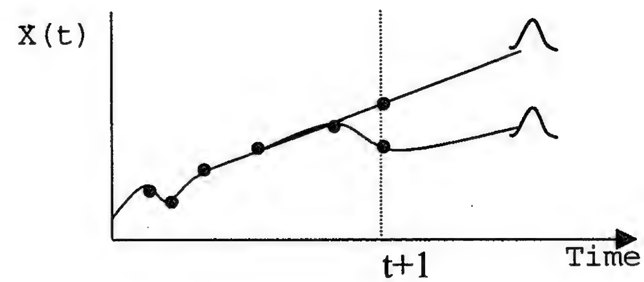
# Additional Forecasting Scenarios

- The following scenarios are expected in forecasting. They are more difficult to map and manage as data structures and require further investigation.

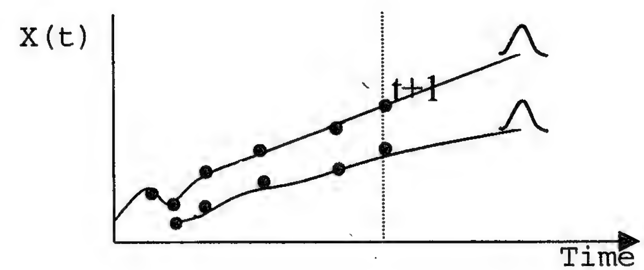
<u>Branching - (Subject of Current Research)</u>

Decision path separation because of budget constraints, shift in requirements, and technological impacts




<u>Parallelism</u>

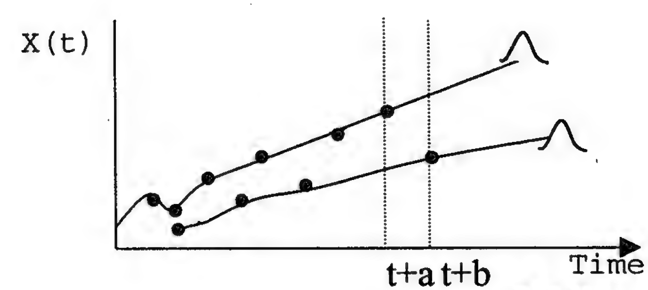
Multiple decision paths can occur during technology trades, bidding, and multi-purpose designs




<u>(A)Synchronization</u>

Decision paths may not be synchronized as tasks are delegated to different groups and technologies are evaluated as they matures

Decision paths may be done independently



# Formulation of a Stochastic Object Framework

- Preliminary Findings
  - Advantages
    - Permit storage of both stochastic and deterministic information
    - Sound temporal framework exists for managing information
  - Disadvantages
    - Assumes time is the axis of change
    - Complex decision making paths difficult to implement and manage
- Characteristics of a Stochastic Object Framework
  - Transaction-Based
    - Allows for non-temporal considerations to affect events; Situation Calculus is necessary for modeling transactions and their relationship to time
    - Multiple axes of change can be modeled
  - Evolutionary
    - Permit storage of deterministic and stochastic information in same structure
    - Permits growth from a data set with few sparse points to a fully populated legacy data history

# More on the Axis of Change

- During the course of the preliminary research, the time axis presented difficulty when time was used as a key for tracking decision making actions. Time is important for forecasting but may not be relevant for:
  - Predictions
  - Comparisons
  - Forecasting across multiple domains
  - Other decision-making processes

- More research needs to be done on quantifying other axes of change.

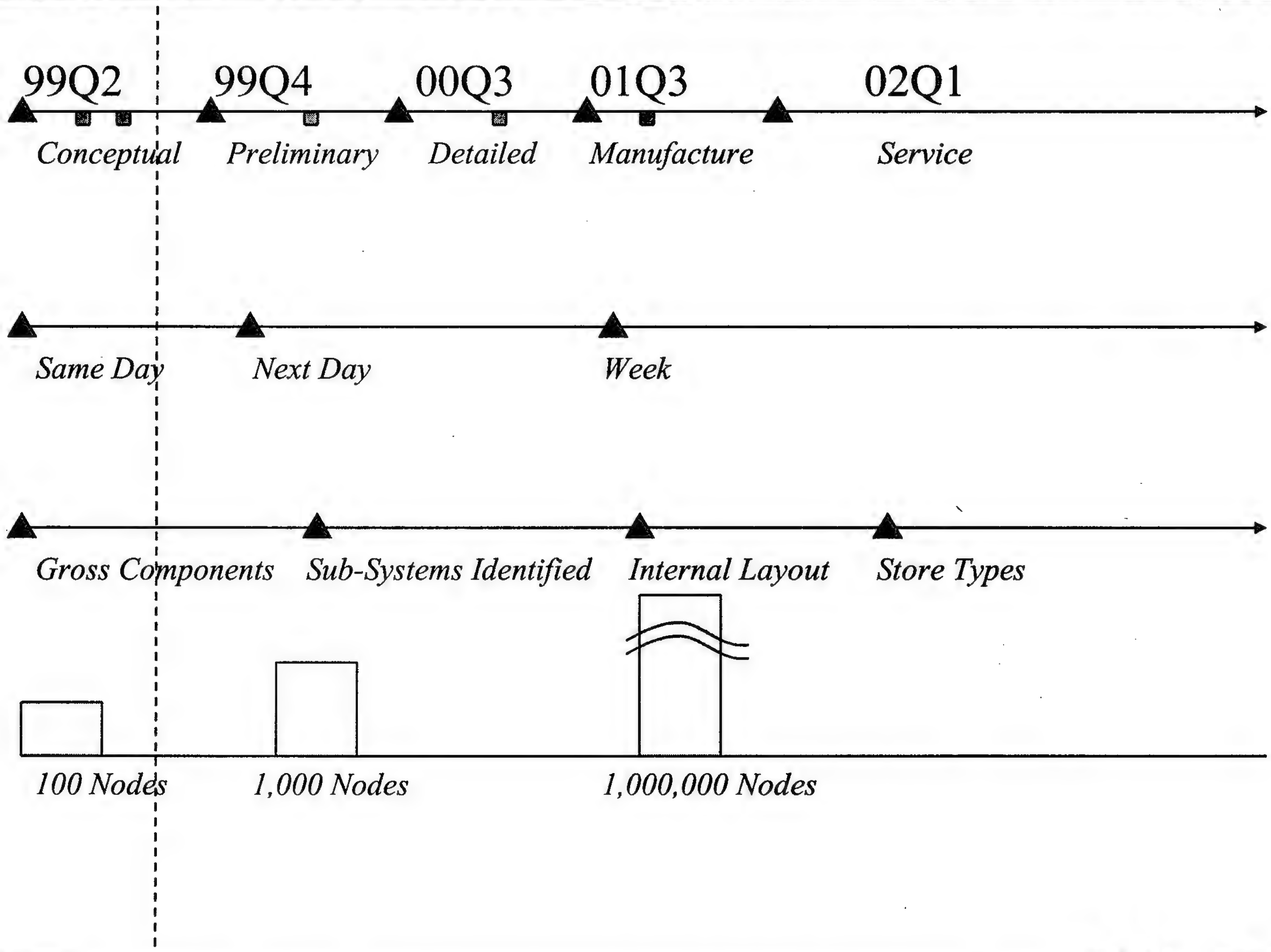
# Some "Axes of Change" within an Enterprise

**Absolute Time**
*How does design compare against the others? Can I down select?*

**Relative Time**
*I've had two hours to get an answer, how does my answer compare?*

**Similarity**
*The other design includes sub-systems, is mine consistent?*

**Model Size**
*My analysis is based on a 200 node FEM and the other is 100 node, should more be used?*





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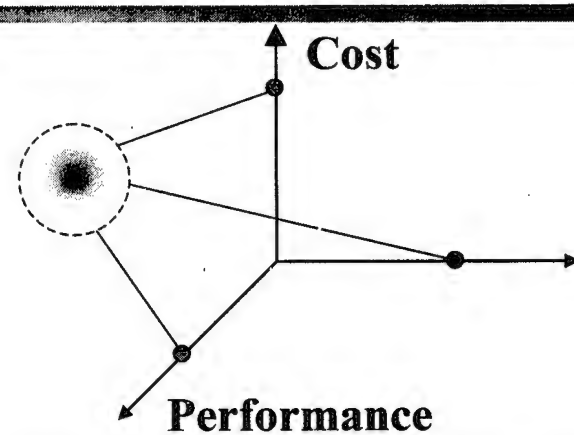
# Summary of Issues

- Tied to Stochastic Modeling
  - Can temporal methods be extrapolated to other axes? How are decisions impacted?
  - Which axis of change is needed for a particular decision type or class?
  - How can decisions be mapped against the axes? How can the axes be mapped against each other?
- Other Issues
  - Investigation into information quantity and quality. How much data is needed? When is extrapolation acceptable?
  - Identify situations where real-time and near real-time information storage are applicable.

# Section 4

# Part D: Decision Tree Networks Research

# Stochastic Decision Trees: Motivation




The dynamics of the future "project (venture) - external environment" system is complex and uncertain. In affordability studies, three classes of metrics are to be taken into account simultaneously: time, cost, and performance.

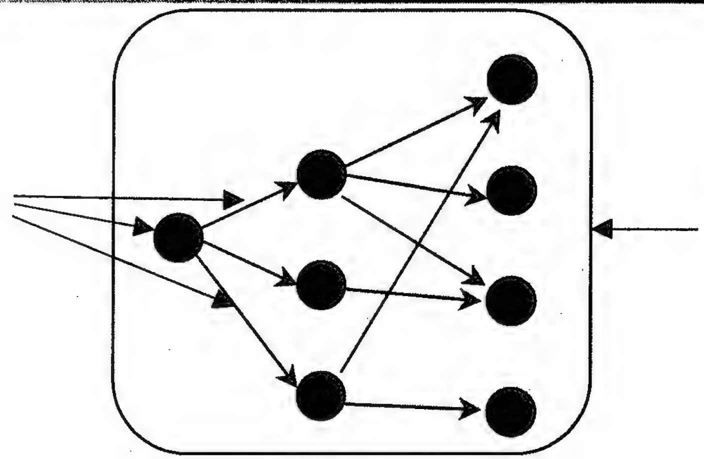
The following types of relationships are characteristic to the system: $\mathbf{T}_i = f(\mathbf{T}_j, \mathbf{C}_k, \mathbf{P}_l)$, $\mathbf{C}_i = f(\mathbf{T}_j, \mathbf{C}_k, \mathbf{P}_l)$, and $\mathbf{P}_i = f(\mathbf{T}_j, \mathbf{C}_k, \mathbf{P}_l)$, where $\mathbf{T}_i$ is time, $\mathbf{C}_k$ is cost, and $\mathbf{P}_l$ is performance of activities (processes) and events (milestones), which constitute the system structure.

This Tri-Variate (Time - Cost - Performance, or **T/C/P**) Affordability Problem needs the metrics on all three axes to be quantified intelligently. The objective of the decision maker is to search for potentially optimal and critical alternatives and paths in the system dynamics.

➡ **Adequate analytical methods are required to derive and examine these relationships in affordability studies**

# Task Connectivity

**TIES Method Output**



**Fuzzy-Stochastic Decision Tree-Network**

## TIES Analysis

* Technology Impact Forecast Equations
* Technology Confidence Estimates (TRLs)
* Feasibility/Viability Estimates

➡ **The TIES method generates input information for the tree-network in form of specifications of activities (processes) and events (milestones)**

## VERT-3F Fuzzy Stochastic Modeling Method

* Information mapping and integration
* Simulation of system's life cycle logic, constraints and objectives (failure and success conditions) using time, cost and performance metrics and their relationships

➡ **Fuzzy-stochastic tree-network models simulate the "project-environment" life cycle dynamics under uncertainty**

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# Project Details (Case Study)

## Project's life cycle phases (network models)

**P1 (N1):** new technologies RDT&E phase
**P2 (N2):** vehicle design phase
**P3 (N3):** test article production, T&E, and certification phase
**P4 (N4):** vehicle production, operation & retirement phase

## New technologies (*T1*, …, *T4*)

***T1***: High-temperature composite wing - to reduce weight and improve temperature tolerance
***T2***: Circulation control - to improve the vehicle's takeoff and landing performance
***T3***: Hybrid laminar flow control - to reduce high-speed flight drag
***T4***: Advanced engine concept - to reduce engine's s.f.c., and noise and emissions levels

## New technologies performance metrics

1. T1 - High-temperature composite wing:
**Y11:** Wing weight reduction, %
**Y12:** Surface work temperature increase, $^{o}K$
2. T2 - Circulation control:
**Y21:** Lift-over-drag force increment, %
**Y22:** Thrust losses, %
3. T3 - Hybrid laminar flow control:
**Y31:** Supersonic drag coefficient reduction, %
**Y32:** Subsonic drag coefficient reduction, %
4. T4 - Advanced engine concept:
**Y41:** Specific fuel consumption reduction, %
**Y42:** Fly-over noise reduction, EPNdB
**Y43:** Side-line noise reduction, EPNdB

## System alternatives (V0, …, V14)

**V0** (baseline) = none of technologies is used
**V1** = T1
**V2** = T2
**V3** = T3
**V4** = T4
**V5** = T1 + T2
**V6** = T1 + T3
**V7** = T1 + T4
**V8** = T2 + T3
**V9** = T2 + T4
**V10** = T3 + T4
**V11** = T1 + T2 + T3
**V12** = T1 + T2 + T4
**V13** = T2 + T3 + T4
**V14** = T1 + T2 + T3 + T4

## System level metrics

| | | | |
|---|---|---|---|
| **1. Flight performance metrics group (M1, …, M4):** | | | |
| **M1:** Landing Approach Speed | $V_{LA}$ | ≤ 155 | kts |
| **M2:** Landing Field Length | LFL | ≤ 11,000 | ft |
| **M3:** Takeoff Field Length | TOFL | ≤ 11,000 | ft |
| **M4:** Takeoff Gross Weight | TOGW | ≤ 1,000,000 | lbs |
| **2. Environmental performance metrics group (M5, M6):** | | | |
| **M5:** Fly-Over Noise (Stage III) | FON | ≤ 106 | EPNdB |
| **M6:** Side-Line Noise (Stage III) | SLN | ≤ 103 | EPNdB |
| **3. Economic performance metrics group (M7, …, M10):** | | | |
| **M7:** Aircraft Acquisition Price | Acq$ | Minimize | FY98$M |
| **M8:** Required Yield per RPM | $/RPM | ≤ $0.13 (*) | FY98$M |
| **M9:** Direct Operating Cost Per Trip | DOC/T | Minimize | FY98$M |
| **M10:** R&D, T&E Costs | RDTEC | Minimize | FY98$M |

# Vehicle's Life-Cycle Tree-Network Models

## N1: New Technologies Research Development, Testing & Evaluation (RDT&E) Phase

SP1: technology feasibility studies → SP2: technology design → SP3: technology test article fabrication → SP4: technology performance testing → SP5: technology time and cost check, and performance evaluation → SP6: alternatives feasibility check

## N2: Vehicle Design Phase

SP1: conceptual design → SP2: preliminary design → SP3: detailed design and systems integration → SP4: system level metrics modeling and simulation and check → SP5: overall performance assessment and decision making

## N3: Test Article Production, Testing, Evaluation and Certification (PTE&C) Phase

SP1: airframe parts manufacturing → SP2: vehicle's systems manufacturing/supply → SP3: components assembly → SP4: final assembly and assembly quality check → SP5: vehicle testing → SP6: performance, time & cost evaluation → SP7: vehicle certification

## N4: Vehicle Production, Operation & Retirement Phase

SP1: vehicle production → SP2: flight operation → SP3: vehicle retirement

# VERT-3 Modeling and Simulation Process

**Step 1. Decision situation formalization**
Define the problem, define success and failure conditions and decision criteria, establish the alternatives to solve the problem

**Step 2. Flow network specification**
Formulate the model, specify main activities and events of the "venture - external environment" system dynamics

**Step 3. Input data collection**
Collect the data on main activities and events, represent the data in the form of probability distributions, histograms, and/or mathematical relationships

**Step 4. Tree-network programming**
Translate the tree-network model into VERT input system, program and debug the model

**Step 5. Network verification and validation**
Verify and validate the model, conduct sensitivity ("what-if") analysis

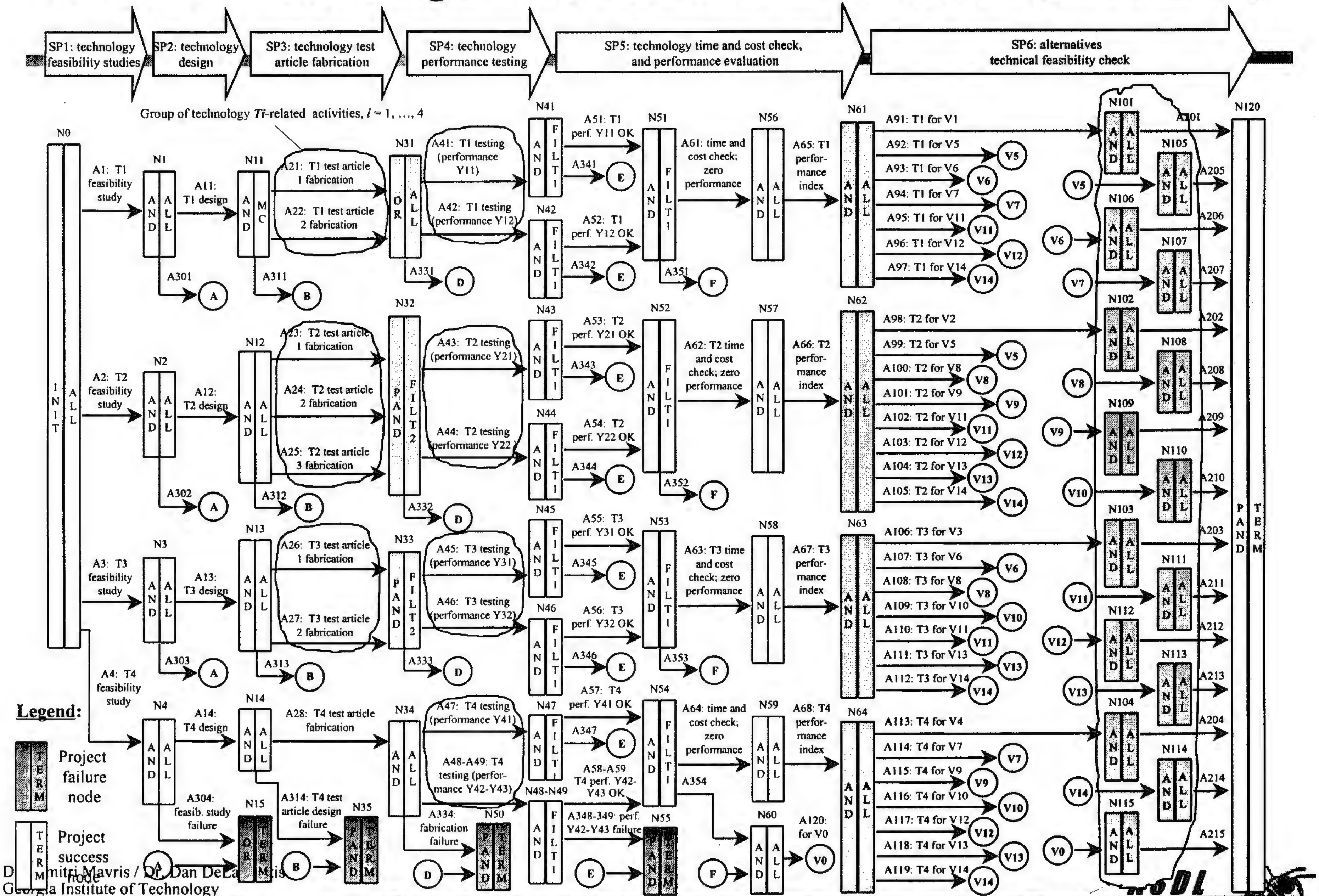
**Step 6. Network simulation and results analysis**
Design the simulation experiments, conduct the experiments, process, and analyze results

**Step 7. Alternatives selection**
Compare alternatives, identify the worst and the best outcomes (critical/optimum paths)

**Step 8. Results generalization and communication**
Present the final study to the decision maker in a concise format; make recommendations regarding those activities and milestones and their parameters, which are time, cost and performance drivers on both critical and winning paths; estimate project's overall risk and success under key uncertainty hypotheses (scenarios)

Iterations are possible

# N1: New Technologies RDT&E Phase Network (Version 2)

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# Section 5

1. *Introduction and Research Setting/Summary*

2. *Overall Technical Approach for Affordable Systems Design*

3. *Methods Implementation and Testbed Applications*

4. *Key Advancements in Method Components*

5. *Conclusions/Summary*

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# Summary of Year 2 Results

1. Significant enhancements to the TIES affordability environment est. in Year 1
   - *Pilot Studies: Environment prototype for Navy's F-18C, NASA's HSCT, a notional 150 pax transport, and a short-haul civil tiltrotor*
   - *JPDM incorporation and validation; n-variate math model constructed*
   - *Genetic Algorithm for technology combinatorial selection problems*
   - *Fuzzy Decision tree constructed to treat stochastic affordable technology selection problem, an evolution of TIES to include schedule/cost as well as performance*

2. Completion of the investigative research into mathematical and soft computing techniques and stochastics, resulting in:
   - *Web-based database of advanced math and soft computing techniques relevant to affordability measurement and prediction, including current investigators, computer codes, and transition status*
   - *Several implementations of methods (Fuzzy sets, GA's, Neural Networks)*
   - *Roadmap towards stochastic methods established, research goals prioritized*

3. A powerful mathematical tool to examine the simultaneous impact of vehicle requirements & technologies has been created and initially tested on a F/A-18C case, including carrier suitability constraints.

4. Methods have been integrated in Graduate level curriculum

# Key Research Innovations

- Recognizing the need for a physics-based, quantitative link between affordability metrics, uncertainty, and technology infusion, the use of disciplinary metric k-factors was a breakthrough in facilitating affordability decision-making
- Recognizing the need for a rapid, accurate assessment of system feasibility and viability, the "5-Step Feasibility/Viability" process, including TIES, was an important breakthrough
- A mathematical environment collecting requirements, design variables, and technologies for simultaneous examination during concept formulation
- Recognizing the need for a probabilistic measure that did not have the shortcomings of traditional arithmetic composite objectives, the JPDM was an important breakthrough
- Finally, the TIES environment was a "integration breakthrough" which incorporates many of the other breakthroughs

# ASDL Gov't/Industry Technology Transfer ('97-'01)

**ONR Code 36**
**Basic Research in Affordability Science**

**(Ongoing and planned)**

| Gov't/Industry | Collaboration/Technology Transfer |
|---|---|
| NAVAIR-Pax River | - Mngt. Briefed; Validation study with F-18 or JPATS |
| NAVSEA-China Lake | - Strong interest in ASDL methods for hypersonic missile |
| NUWC | - ASDL methods for torpedo validation and design app. |
| STTR | - Affordability for Surface Combatants |
| STTR | - Simulation-Based Acquisition, Affordability Science |
| Lockheed Martin (Ft Worth) | - UCAV Technology Impact Forecast (TIF) |
| | - Manufacturing (JSF) |
| Boeing (St. Louis)/DARPA | - Application to Study of Synthetic Jet Tech. |
| Boeing (Long Beach) | - *MUST* Cost Initiative for C-17 |
| NASA Langley SAB | - HSCT TIF, Subsonic Transport TIF |
| | - Goal-Based Outcome Study |
| Air Force Research Laboratory | - UCAV TIF |
| ONR/Boeing/Lockheed | - Composite Affordability Initiative |
| Rolls-Royce Allison | - T-406/V-22 TIF |
| General Electric Aircraft Engines | - Robust Design Simulation Applications |

# Grant Publications Update (June 98 through Oct. '99)

Journal Articles submitted and accepted:

1. Mavris, D.N., DeLaurentis, D.A., Bandte, O., Hale, M.A., "The Role of AI in a New Virtual Aircraft Design Environment," accepted and to be published in special issue of *Engineering Applications of Artificial Intelligence* (EAAI), estimated publication in early 2000.

Conference Papers presented and in process of submittal to Journals in '99:

1. Mavris, D.N., DeLaurentis, D.A., "A Stochastic Design Approach for Aircraft Affordability," 21st Congress of the International Council on the Aeronautical Sciences (ICAS), Melbourne, Australia, September 1998. ICAS-98-6.1.3. *(intended for AIAA Journal of Aircraft)*

2. Bandte, O., Mavris, D.N., DeLaurentis, D.A., "Determination of System Feasibility and Viability Employing a Joint Probabilistic Formulation", 37th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 11-14, 1999. AIAA 99-0183. *(intended for AIAA Journal of Aircraft)*

3. Mavris, D.N., Kirby, M., Qiu, S., "Technology Impact Forecast for a High Speed civil Transport," AIAA/SAE World Aviation Congress and Exposition, Anaheim, CA, September 28-30, 1998. AIAA-98-5547. *(intended for ... TBD)*

4. Daberkow, D.D., Mavris, D.N., "New Approaches to Conceptual and Preliminary Aircraft Design: A Comparative Assessment of a Neural Network Formulation and a Response Surface Methodology", World Aviation Congress and Exposition, Anaheim, CA, September 28-30, 1998. SAE-985509. *(intended for ... TBD)*

5. Mavris, D.N., Kirby, M., "Technology identification, Evaluation, and Selection for Commercial transport Aircraft," for presentation at 58th annual conference of Society of Allied Weight Engineers, May 1999.

To be presented:

1. Mavris, D.N., Daberkow, D.D., "Knowledge Representation, Utilization and Reasoning in the Conceptual Aircraft Design Process," Abstract submitted to the World Aviation Congress, San Francisco, CA, Oct. 19-21, 1999.

2. Mavris, D.N., Kirby, M.R., Daberkow, D.D., "Technology Evaluation and Selection via a Genetic Algorithm Formulation for Aerospace Systems," Abstract submitted to the World Aviation Congress, San Francisco, CA, Oct. 19-21, 1999.

# ONR Grant: ASDL Ph.D. Student/Staff Support

Number of Ph.D. Students Supported: 8

| | |
|---|---|
| Ms. Debora Daberkow (ASDL) | Mr. Oliver Bandte (ASDL) |
| Ms. Danielle Soban (ASDL) | Mr. Andy Baker (ASDL) |
| Ms. Elena Garcia (ASDL) | Ms. Linda Wang (ASDL) |
| Ms. Shobana Murali (Math) | Mr. Noppadon Khiripet (EE) |

Number of Masters Students Supported: 8

Multidisciplinary Professional Team: 8

| | |
|---|---|
| Dr. Dimitri Mavris (AE) | Dr. Daniel DeLaurentis (AE) |
| Dr. Dan Schrage (AE) | Dr. Mark Hale (AE) |
| Dr. Leonid Bunimovich (Math) | Dr. George Vachtsevanos (EE) |
| Dr. Jimmy Tai(AE) | Dr. Ivan Burdun (AE) |

+ ***Over 40 students exposed to methods in graduate design curriculum***

# Some Future Plans

**Stochastic Affordability Prediction; Decision Making**

- Continued Development of TIES
- Validation Studies (Collaboration with Navy Centers)
- Application of methods to new systems for Navy

**Evolutionary technology, system fitness, resource allocation**

- Mathematical Modeling/Solution for Military A/C Requirements
- Technology Landscapes

[redacted]

- Develop methods for revolutionary technological change

# REPORT DOCUMENTATION PAGE

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**14. ABSTRACT**

Four scientific tasks are performed in response to the Office of Naval Research's (ONR) Affordability Measurement and Prediction Broad Agency Announcements (BAA). These tasks complement the ONR's overall objective of addressing affordability through a combination of non-deterministic procedural analysis and fuzzy, cross-functional integration and synthesis. *This research provides the ONR with an initial capability to measure and predict affordability.* These scientific tasks should not be examined in isolation, rather, they are envisioned as key components of a comprehensive Design for Affordability environment, called the Virtual Stochastic Life Cycle Design Environment.

**15. SUBJECT TERMS**
Affordability, Decision-Making, Stochastic, Probabilistic, Uncertainty

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